PHD

Voltage Control in Distribution Networks using On-Load Tap Changer Transformers

Gao, Chao

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Voltage Control in Distribution Networks using On-Load Tap Changer Transformers

By

Chao Gao

BEng

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Abstract

Voltage is one of the most important parameters for electrical power networks. The Distribution Network Operators (DNOs) have the responsibility to maintain the voltage supplied to consumers within statutory limits. On-Load Tap Changer (OLTC) transformer equipped with Automatic Voltage Control (AVC) relay is the most widely used and effective voltage control device.

Due to a variety of advantages of adding Distributed Generation (DG), more and more distributed resources are connected to local distribution networks to solve constraints of networks, reduce the losses from power supply station to consumers. When DG is connected, the direction of power flow can be reversed when the DG output power exceeds the local load. This means that the bidirectional power flow can either be from power grid towards loads, or vice versa. The connection point of DG may suffer overvoltage when the DG is producing a large amount of apparent power. The intermittent nature of renewable energy resources which are most frequently used in DG technology results in uncertainty of distribution network operation. Overall, conventional OLTC voltage control methods need to be changed when DG is connected to distribution networks. The required voltage control needs to address challenges outlined above and new control method need to be formulated to reduce the limitations of DG output restricted by current operational policies by DNOs.

The thesis presents an analysis of voltage control using OLTC transformer with DG in distribution networks. The thesis reviews conventional OLTC voltage control schemes and existing policies of DNOs in the UK. An overview of DG technologies is also presented with their operation characteristics based on power output. The impact of DG on OLTC voltage control schemes in distribution networks is simulated and discussed. The effects of different X/R ratio of overhead line and underground cable are also considered. These impacts need to be critically assessed before any new method implementation.

The thesis also introduces the new concepts of Smart Grid and Smart Meter in terms of the transition from passive to active distribution networks. The role of Smart Meter and an overview of communication technologies that could be used for voltage control are investigated. The thesis analyses the high latency of an example solution of which cost and availability are considered to demonstrate the real-time voltage control using Smart Metering with existing communication infrastructures cannot be achieved cost-effectively.

The thesis provides an advanced compensation-based OLTC voltage control algorithm using Automatic Compensation Voltage Control (ACVC) technique to improve the voltage control performance with DG penetration without communication. The proposed algorithm is simulated under varying load and DG conditions based on Simulink MATLAB to show the robustness of the proposed method. A generic 11kV network in the UK is modelled to evaluate the correct control performance of the advanced voltage control algorithm while increasing the DG capacity.

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List of Abbreviations

AC	Alternation Current
ACVC	Automatic Compensation Voltage Control
ADN	Active Distribution Network
ANN	Artificial Neural Network
AVC	Automatic Voltage Control
AVRS	Automatic Voltage Reference Setting
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CT	Current Transformer
DC	Direct Current
DDPMG	Direct-Drive Permanent Magnet Generator
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
DSL	Digital Subscriber Line
DUKES	Digest of United Kingdom Energy Statistics
EHV	Extreme High Voltage
ENA	Energy Network Association
ESQC	Electricity Safety, Quality and Continuity Regulations
ESR	Electricity Supply Regulations
FACTS	Flexible AC Transmission Systems
GDS	Generic Distribution System
GT	Grading Time
HAN	Home Area Network
HV	High Voltage
ICE	Internal Combustion Engine
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
LAN	Local Area Network
LDC	Line Drop Compensation
LV	Low Voltage
MCFC	Molten Carbonate Fuel Cell
MIMO	Multiple Input Multiple Output
MPT	Maximum Power Tracker

NO_2	Nitrogen Dioxide
NO_X	Oxynitride
NRC	Negative Reactance Compounding
OFGEM	Office of Gas and Electricity Market
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
PEM	Polymer Electrolyte Membrane
pf	power factor
PLC	Power Line Carrier
PT	Potential Transformer
pu	per unit
PV	Solar Photovoltaic
QoS	Quality of Supply
R	Resistance
RO	Renewable Obligation
rpm	revolutions per minute
RTDS	Real Time Digital Simulator
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SDC	Source Drop Compensation
SE	State Estimation
SOFC	Solid Oxide Fuel Cell
SO_X	Oxysulfide
STATCOM	Static Synchronous Compensator
STC	Standardized Test Conditions
TAPP	Transformer Automatic Paralleling Package
UHF	Ultra High Frequency
WAN	Wide Area Network
WiMAX	Worldwide interoperability for Microwave Access
WLAN	wireless local area network
Wp	Watts peak
X	Reactance
X/R	Reactance to Resistance Ratio

Chapter 1

Introduction

This chapter is a general introduction to the thesis, voltage control in distribution networks using On-Load Tap Changer (OLTC) transformers with Distributed Generation (DG). The background of this thesis starts with a brief description of the UK electricity networks, statutory voltage limits in the UK and the basic OLTC transformer with Automatic Voltage Control (AVC) relay operation. The overview of advantages and disadvantages of DG and the voltage control perspective in the future Smart Grid are introduced then the possibility of active voltage control using Smart Meters with existing communication technologies are investigated. The increasing level of DG penetration and potential voltage control problems caused by DG on distribution networks are explored which are required to be addressed by DNOs. An advanced compensation-based OLTC voltage control algorithm is proposed which promises to accommodate DG penetration as the main contributions of the thesis.

1.1 Background

Electrical power systems have been developed base on large power stations which contain large power generators at a smaller number of sites since 1882. Transmission system is a long-distance bulk network through which electrical power moved at extra high voltages (400kV and 275kV) from large power generation stations to the lower voltage distribution networks and to a small number of large industrial customers. The voltage is stepped up to high voltage and extra high voltage levels in these centralized stations. Distribution networks carry the electrical power from transmission network and then deliver to the end users at a lower voltage and more localized networks (from 132kV to 400V). The high-voltage power from the transmission networks is converted and distributed to Extreme High Voltage (EHV) 132kV and 33kV, High Voltage (HV) 11kV and 6.6kV and Low Voltage (LV) 400/230V distribution networks through interconnected transmission and distribution networks. Finally the power is distributed to individual consumers from radial low voltage distribution networks as shown in Figure 1.

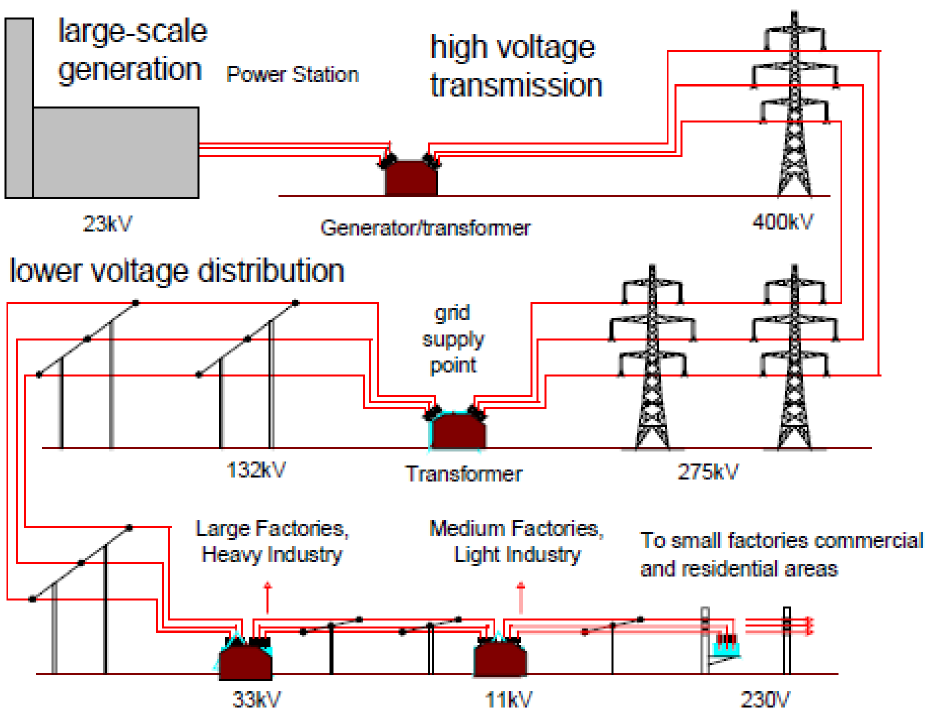


Figure 1. UK electricity networks [1]

The Distribution Network Operators (DNOs) have the responsibility to regulate and maintain the voltage profile supplied to customers within statutory limits which are defined in Electricity Safety, Quality and Continuity Regulations (ESQC) 2002 [2]. In the UK, the LV network supplies voltage to consumers at 400/230V with +10/-6% of upper and lower limits while HV network (11kV and 6.6kV) with ±6% of upper and lower limits [3]. The OLTC transformer equipped with AVC relay is the voltage control device to satisfy these requirements under different voltages and load conditions. It was more than 80 years ago OLTC was introduced to power transformers as a means of on-load voltage control. Today, about 96% of power transformers above 10MVA contain OLTC [4].

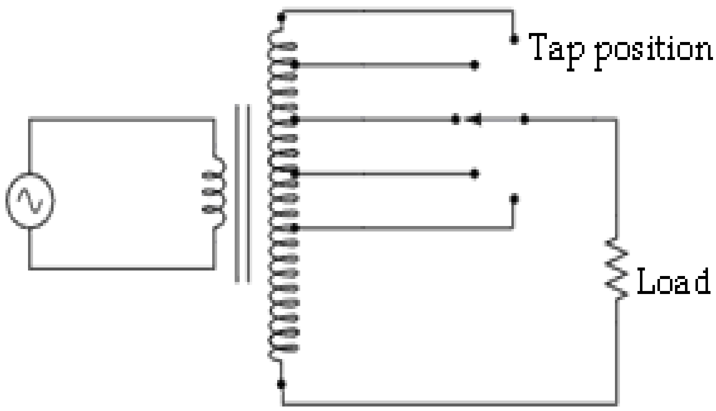


Figure 2. OLTC mechanism

The OLTC voltage regulation is naturally operated by changing the number of turns in one winding of transformer to physically alter the ratios of the transformer. More or less windings can be switched into power system by OLTC transformer to the alteration of ratios and therefore affects control of the transformer secondary voltage to keep the voltage value within required limits as shown in Figure 2 [5]. The UBB type OLTC product from ABB company is presented as an example in Figure 3 [6].

Figure 3. ABB OLTC type UBB [6]

The OLTC mechanism is a transformer component automatically controlled by a relay to increase or decrease voltage by altering tap positions of transformer. When the secondary voltage detected is outside the permitted deadband, the relay issues a command to the tap changer mechanism to alter its tap position in order to restore the required voltage level. The OLTC transformer, coupled with its voltage control relay regulates the transformer output voltage to keep the voltage magnitude within limits. It is generally used in the distribution networks to transform from EHV (132kV and 33kV) down to HV (11 or 6.6kV) [7].

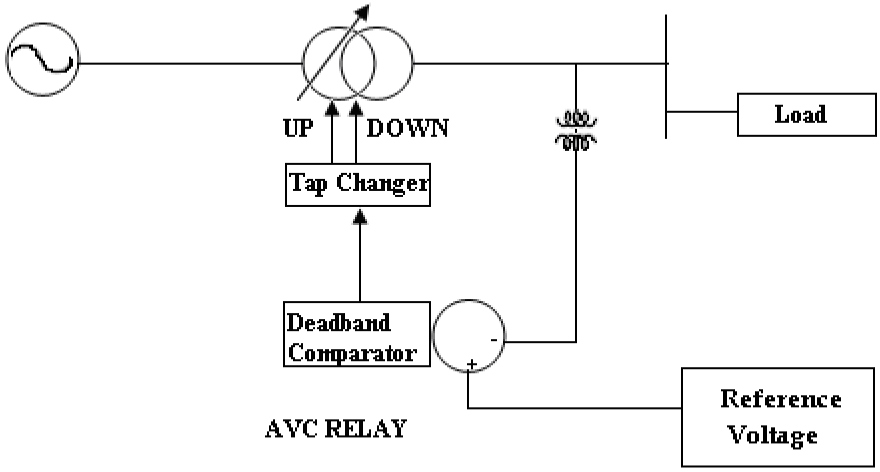


Figure 4. AVC relay scheme

A block diagram illustrates the basic operation and the general arrangement of OLTC and a simple AVC relay which is shown in Figure 4. The AVC relay monitors the voltage at the secondary side of the transformer. With the comparison between load voltage and reference voltage, the AVC relay determines whether to adjust the tap position or not in order to maintain the required voltage level. For short duration voltage excursions outside of the voltage deadband, a time delay is introduced into the AVC relay to prevent the operation of tap changer [8].

1.2 Motivation

Over the last few years, the interest in use of DG connected to local distribution networks has grown and is continuing to grow. The DG has some major advantages such as environmentally friendly power supply, reduction of losses for power transmission, liberalization of electricity markets and reduction of fossil fuel resources [9-12].

However, since distribution networks become more complex and the number of DG is continuing to grow, conventional OLTC voltage control schemes are less effective. The DG might change the power flow so that it can no longer be considered as unidirectional in distribution networks. From another point of view, distribution networks have been designed based on the assumption that power flow is unidirectional only from grid to load for many years [13-16]. When DG is operating, the voltage of the DG connection point can rise to an unacceptable level. Therefore, the presence of DG, especially when DG output power is large, will obviously impact distribution system operation and control.

With the growing power demand and increasing use of renewable energy, the traditional electricity network will be developed from a passive network to an active network. Many countries propose a "Smart Grid" concept that is a more efficient power grid by using smart devices, communication systems and power management systems. These require a larger monitoring capacity, advanced analysis facilities to support system control, enhanced power security and effective communication to meet power demand as well as reduce energy consumption and cost. The possibility of cost-effective real-time voltage control using smart meters needs to be critically assessed by analysing the latency and cost of Smart Metering system with available communication infrastructures to demonstrate that the voltage control using smart meters cannot be achieved in the next few decades to come.

Under these situations, DNOs need a more effective OLTC voltage control scheme to accommodate the voltage problems associated with increasing penetration of DG in a cost-effective way.

1.3 Objectives

The first objective is to assess the impacts of DG on OLTC voltage control in HV distribution networks. A comprehensive analysis of different DG technologies impacts on OLTC voltage control will be simulated under various network conditions in Simulink Matlab.

Another objective of the thesis is to show the real-time voltage control using smart meters in distribution network cannot be achieved in a cost-effective way with the existing communication technologies. The latency and cost of a generic distribution network with available communication network example will be investigated which is too high to meet the requirement of real-time voltage control in smart grid.

The main objective is to propose an advanced OLTC voltage control method which is in order to maximise the available capacity of the existing network infrastructure and support the DG penetration by dynamically change the reference voltage setting point to maintain all voltage within limits. Under different load and DG conditions, a higher reference voltage is applied to compensate the voltage drop along the feeders. A lower reference voltage at a substation can be applied to avoid overvoltage and more voltage headroom is available for further DG penetration when voltage drop along the feeders is less significant or there is voltage rise situation. The proposed method will be tested using

Simulink Matlab with a series of generic 11kV distribution networks in the UK.

1.4 Challenges

Worldwide, the amount of electrical power demand is continuing to grow every year. The quality and reliability of power supply is the essential requirement for electrical power systems. At the same time, in order to achieve the 80 per cent all carbon emissions reduction target by 2050, as stated in the "Low Carbon Transition Plan", July 2009 [17], the UK's electrical power generation sources will be changed from coal and gas to renewable energy sources. The increasing penetration of renewable energy is necessary to reduce environmental impacts. This will involve a large amount of DG that will be connected directly at local distribution networks to solve the constraints of distribution networks. This will help reduce the transportation cost from power supply stations to consumers and enable exploit the renewable energy in the future. With low level of penetration (about 15% of peak demand or less), the influence of DG is not significant to networks because of the proper protection at the point of interconnection [18]. The presence of high level DG integration has considerable impact on voltage regulation of existing OLTC voltage control system due to their complex nonlinear characteristics [19].

For a one-line distribution feeder with one DG, the voltage drop on the feeder can be approximated by equation (1)

$$\Delta V = V_1 - V_2 \approx \frac{R_{LN}(P_L - P_{DG}) + X_{LN}(Q_L - (\pm Q_{DG}))}{V_2} \tag{1}$$

where P_L,P_{DG}, Q_L, Q_{DG} are active and reactive power of load and DG respectively, R_{LN}, X_{LN} are the line impedance, V_1, V_2 are the sending-end voltage and load bus bar voltage respectively [14].

When DG output power exceeds the local loads, the power flow will be reversed thus the distribution networks can no longer be considered with unidirectional power flow. Since mostly voltage control schemes operated based on a fact that voltage decreases along feeder, the high penetration of DG will impact voltage control accuracy. This depends on the DG output power relative to the load active and reactive power and the X/R ratio of feeder [20]. Thus the feeder currents measured by traditional AVC relay are no longer proportional to load currents. The measured voltage is shifted upwards or downwards depending on the power factor of transformer current and direction of power flow to the DG and load [21]. When DG is operating, the voltage of DG connection point can rise above the statutory limits, higher than the sending-end busbar voltage. When the voltage of the DG connection point reaches the network statutory limits, the DG output must be constrained. This method limits the power output from DG and thus makes DG less competitive. Different DG techniques have their characteristics and the impacts on OLTC voltage control is needed to be assessed. Since distribution networks can use either underground cable or overhead line to transfer electrical power, the different X/R ratio of these two lines can lead to different voltage control problems. The effective control of the OLTC with DG under different constructions in distribution network is the major challenge to maintain the voltage within limits in the meantime maximizes the DG output power.

A Smart Grid is more consumer-interactive in order to make the grid truly intelligent. There are many challenges and problems which need to be addressed with the emergence of Smart Grid. The renewable energy resources will be used more and more such as wind, solar and hydrogen and result in the consumer integration inevitable to aid the grid performance. Therefore, a high degree of DG penetration will occur due to the high efficiency and low environmental impact of these preferred DG resources.

Power quality monitors have been recommended to be installed at substation, middle of feeder, end of feeder and near sensitive loads in distribution networks. However, this kind of monitors do not have the capability of monitoring system attributes such as voltage, current, and power flow at substations, customer meters and distribution switching devices [22]. The Smart Meter used in the UK is a new generation of electricity and gas meters which can only display the energy consumed and communicate directly the information with energy supplier for billing use. Nevertheless, the Smart Meter is intended to offer a range of intelligent functions in the future such as near real-time information on energy use and intelligent local load management. However, the Smart Meter does not have the capability to control voltage and the monitoring capability of Smart Meters to be used for voltage control has not yet been considered. The latency and cost of different communication technologies operated with Smart Meters in order to participate in voltage control for distribution networks require further investigation to demonstrate these performance of the innovations.

1.5 Contribution

The research presents an overview of existing OLTC voltage control techniques. The DG impacts on OLTC voltage control is analysed according to different types of DG with their typical operational characteristics. The different types of network construction using overhead lines or underground cables which have different X/R rations have been simulated to demonstrate the impacts on voltage control in distribution networks.

The concepts of Smart Grid and Smart Meter offer the potential opportunity to improve voltage control performance in distribution networks. Since the existing OLTC voltage control has not considered Smart Grid techniques and has lacked of capability to be operated in a coordinated manners. An overview of voltage control concept using different communication technologies and Smart Meters in the future power system has been presented. The latency and cost of each existing communication technologies and the potential possibilities of real-time voltage control function using Smart Meters have been investigated to demonstrate the potential for real-time voltage control function. Based on current concepts, it has been concluded that they will not be provided by Smart Metering system in the UK due to high latency and high costs in the short-term.

A novel approach of OLTC voltage control, Automatic Compensation Voltage Control (ACVC), with the presence of DG is proposed to accommodate voltage rise problems caused by DG together with the bidirectional power flow are investigated considered. The benefit of this voltage control method is that it can be used under different conditions, using simple relations of power flow direction and reference voltage setting point. This method reduces the design development cycle, simplifies design complexity and improves control performance. An advanced compensation-based OLTC voltage control algorithm in distribution network is based on the ACVC technique which is centred on the control of OLTC transformers and is aimed at addressing voltage control problems caused by high level of DG penetration. More DG can be integrated into the networks with the proposed OLTC algorithm.

A series of generic test models for the advanced compensation-based OLTC voltage control algorithm with DG penetration have been developed in Simulink of MATLAB® software. The output power of the equivalent DG model is controlled when the DG operation characteristics do not need to be considered. This advanced control algorithm is simulated under various DG conditions by these generic distribution network models to demonstrate its performance under complex power system conditions.

1.6 Outline

Chapter 1 is the general introduction of the thesis.

Chapter 2 gives an overview of different OLTC voltage control technologies in conventional distribution networks. Literature reviews on different OLTC voltage control methods and other control devices are presented.

Chapter 3 introduces a brief overview of different DG technologies with their operation characteristics based on power output. The scales and developed potentials of DG capacity are presented with barriers of different technologies.

Chapter 4 introduces the new concepts of Smart Grid on voltage control in distribution networks and the role of Smart Meter in active distribution networks on improving voltage control performance. An overview of voltage control concept using Smart Metering system in the UK has been briefly presented. Different communication technologies are summarized then the latency and cost of example communication network operated with Smart Meters is investigated to demonstrate the possibility of real-time voltage control by the existing communication technologies.

Chapter 5 provides the analysis on how the presence of DG will impact on OLTC voltage control technologies presented in Chapter 2. It starts with a basic overview on the possible impact of different DG technologies on

OLTC voltage control and this has then examined by comparative analysis using Simulink of MATLAB®. The different impacts of overhead line and underground cable on voltage in distribution network have also been simulated.

Chapter 6 illustrates an advanced compensation-based OLTC voltage control algorithm using ACVC method in 11kV distribution networks with the penetration of DG.

Chapter 7 provides a series of sensitive simulation studies to test the proposed OLTC control algorithm. Both cases, without and with DG involved in the proposed voltage control algorithm have been examined. The case of DG with varying power output has also been included. An automatic voltage setting point was provided by the proposed control algorithm with DG output maximization as the objective. A selection of simulation studies based on Simulink of MATLAB® has been analysed using a series of 11kV distribution network models.

Chapter 8 presents conclusions.

Chapter 9 recommends the future works.

Chapter 2

Voltage control technologies in conventional distribution networks

This chapter describes voltage control technologies using OLTC in conventional distribution networks without DG connection. It starts with basic information of statutory voltage requirements in the UK distribution networks and then how OLTC is operated. The different OLTC voltage control methods and other voltage control devices are also presented.

2.1 Introduction

Voltage and frequency are the primary factors in the Quality of Supply (QoS) for power distribution networks. In distribution networks, only voltage control is considered since supply frequency is generally controlled at the transmission level [23].

Before 1994, the permitted voltage limits of distribution networks below 132kV were all ±6% by Electricity Supply Regulations (ESR). In order to harmonise the power systems in the UK with the power systems in Europe, the ESR is amended that the steady-state voltage magnitudes of power systems are required to be maintained within ±6% of nominal voltage for systems above 1kV and below 132kV and for voltage level of systems between 50V and 1kV, the permitted statutory limits have +10%/-6% of nominal voltage. The original effective date of ESQC is Oct 2001 but due to a large amount of comments made during the consultation process, the ESQC 2002 went into effect from Jan 2003 to replace the ESR in the UK. The permitted voltage limits are not changed in the ESQC 2002 thus the LV distribution network supplies voltage to consumers at 400/230V with +10/-6% of upper and lower limits while HV distribution network (11kV and 6.6kV) with +/-6% of upper and lower limits. However, voltage limits have been often be kept within ±3% of nominal value in 11kV networks when they are designed at the planning stage in order to maintain the voltage of load in LV networks within statutory limits +10% and -6% [24].

Electrical power is supplied from high voltage transmission networks and then converted to low voltage customers via distribution networks. DNOs are under obligation by the ESQC to provide the voltage maintained within certain limits to their customers across distribution networks under different situations so that the various characteristics of devices can be able to accommodate the permitted voltage limits by different customers. The changing of load or the integrations of DG can cause the voltage profile of distribution networks to be changed while DNOs ensure the systems are under operation within permitted voltage limits to avoid complain from their customers [25]. The transformers employing the tap changers in the form of inter bus transformers or booster transformers have been the main equipment to control voltage and maintain it in electrical power systems for many years [26]. The so called tap changer is a device attached to the power transformer for standard regulation of the secondary voltage of transformer. The inter bus transformers interconnecting 400kV, 275kV and 132kV systems to transfer massive electrical power between different voltage levels, therefore the additional cost of equipping a tap changer in the transformer design is relatively minor. Tap changers can be on-load or off-load. In the UK, 11kV distribution network is the lowest voltage level system that contains transformers with on-load tap changers to provide voltage control function without interruption. The OLTC transformers and AVC relays are widely used as voltage control devices that can be controlled locally or remotely in HV distribution networks [26]. The OLTC voltage control with the associated AVC relay has a variety of voltage control features includes Line Drop Compensation (LDC) to ensure that the voltage can be controlled not only at transformer terminals but rather at a nominal supply point. Circulating current compensation techniques have been used to avoid complications when transformers are operated in parallel and Grading Time (GT) has been used to accommodate series operation of transformers [27].

2.2 Basic operation of OLTC

The OLTC is used to change tap position which is the connection point along transformer winding while the transformer is on-load without a supply interruption to provide a direct control. There are two types of tap changer that mainly used in the UK substations of 33/11kV networks. The resistor type is classified as either double resistor or single resistor arrangements [28]. The tap changer generally has the new connection before releasing the old one by using multiple tap selector switches as shown in Figure 5. High circulating currents are avoided by using a diverter switch to temporarily place large diverter impedance in series with the short-circuited turns [29]. The basic operation of OLTC is described using the typical two resistor configuration of OLTC shown in Figure 5 below. In order to switch less winding from start statement that the tap changer is at position 2 to move to tap position 3 with load connection, operation process is as follows.

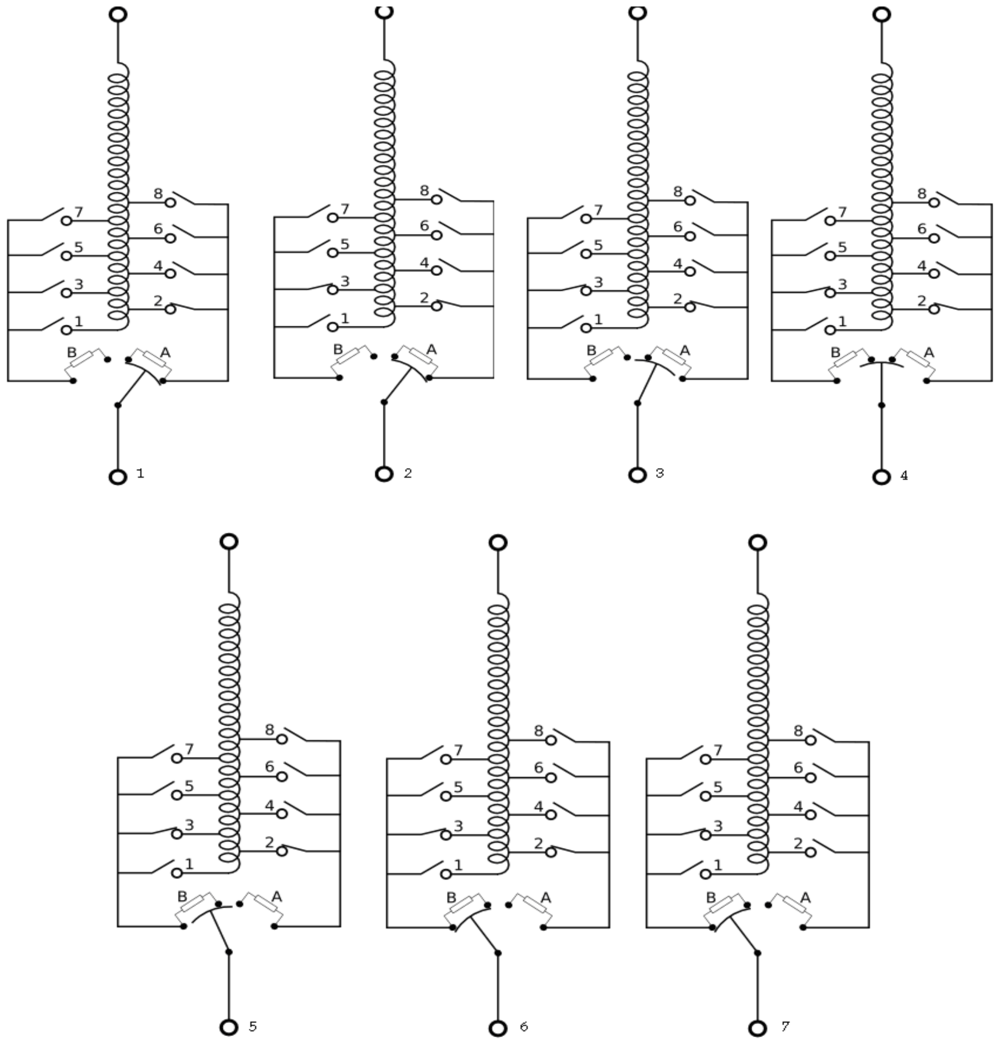


Figure 5. Basic operation of OLTC [30]

1. Switch 2 closed and other switches are opened. Diverter resistor A is short-circuited by rotary switch and diverter B is unused.

2. Switch 3 closes by an off-load operation.

3. Rotary switch moves left and disconnects the right connection. The load current is conducting through diverter resistor A.

4. Rotary switch moves left and connects both contacts A and B. Load now supplied via diverter resistors A and B, winding turns bridged via A and B.

5. Rotary switch moves left and disconnects contact with diverter A. Load now supplied via diverter B only, winding turns no longer bridged.

6. Rotary switch moves left and shorts diverter B. Diverter A is unused now.

7. Switch 2 opens by an off-load operation.

Then the operation is completed that the tap position is changed from 2 to 3 and less winding are switched [30].

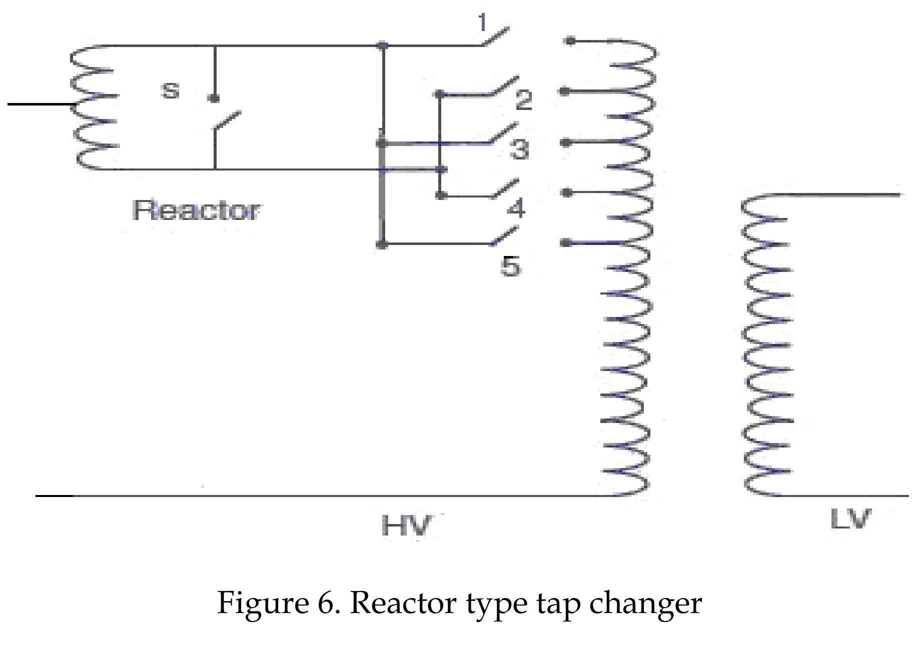


Figure 6. Reactor type tap changer

The operation of reactor type tap changer is shown in Figure 6. This method uses an auxiliary reactor (S is the switch across the reactor) to assist tap changing. The reactor has a centre tapped winding on a magnetic core. The two ends of the reactor are connected to the two bus bars. The two bus bars have odd/even numbered tap switches are connected to them.

To move from tap 1 to tap2, the shorting switch S is closed when only tap 1 is connected to the reactor to minimize the drop in the reactor. Then the tap switch 2 is closed and the S is open. When the both ends of reactor are connected to two successive taps, the switch S must be kept open for limiting the circulating current by the reactor. The tap switch 1 is open then the S is closed. The tap changing operation is therefore completed [31].

2.3 Line Drop Compensation

An OLTC is normally provided with LDC function in order to keep the voltage at a remote point constant without using any communication link. LDC monitors the voltage at secondary side of transformer and then using a measure of secondary current to simulate the voltage drop across feeder that exists between transformer and load as described by equation [29]:

$$V_M = V_S - \Delta V \approx V_S - I_L Z_{SET} = V_S - I_L (R_{SET} + jX_{SET}) \tag{2}$$

where V_M and V_S are the measure voltage of load and sending-end voltage respectively, I_L is the current through OLTC transformer and R_{SET}

and X_{SET} are the LDC resistive and reactance compensation setting.

This voltage drop ΔV along the feeder impedance (line resistance *R* and line reactance *X*) is used to boost the voltage regulated at transformer terminal therefore ensuring the correct voltage level maintains at load where it is required.

In conventional distribution networks, the voltage of load at a remote point V_M is controlled by LDC to V_{SET} ± deadband by altering the tap position of OLTC, where V_{SET} is the magnitude of reference voltage setting point that is required to be controlled at load busbar and deadband is the bandwidth of AVC Relays. Generally, a range of 1% to 3% of the base voltage is selected to be the deadband [32]. When $V_S - \Delta V$ is higher than V_{SET} + deadband or lower than V_{SET} – deadband, the tap position is changed by operation of OLTC to maintain V_M be a required magnitude. The LDC provides voltage control at a nominal load point rather than at the transformer's terminal as shown in Figure 7. Properly adjusting *R* and *X* to the turns ratios of Current Transformer (CT) and Potential Transformer (PT) yields

$$R_{SET} = \frac{N_{CT}}{N_{PT}} R \tag{3}$$

$$X_{SET} = \frac{N_{CT}}{N_{PT}} X \tag{4}$$

where R_{SET} and X_{SET} are LDC simulated R and X settings for the resistive/reactive compensation. N_{CT} is the turn's ratio of CT and N_{PT} is turn's ratio of PT.

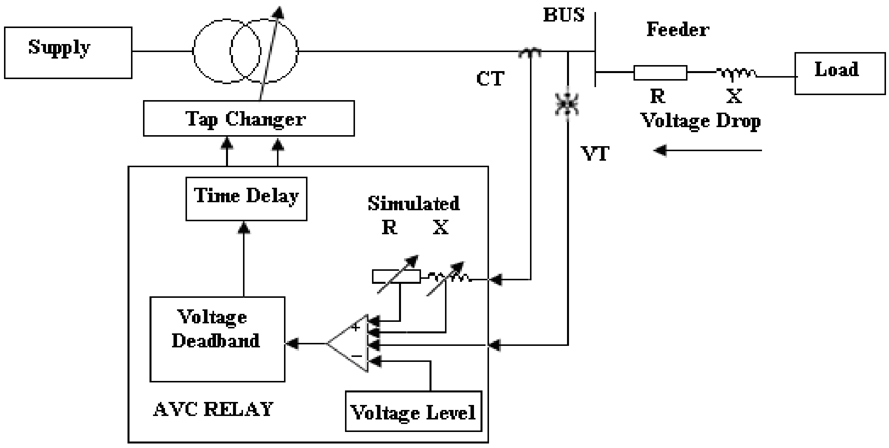


Figure 7. AVC relay scheme with LDC

In most of LDC voltage regulation, the internal setting coefficients of feeder impedance can be obtained from sending-end busbar voltage for bank current with power factor angle at peak load as well as at light load as the follow equations [33]. This data can be provided from off-line power flow studies and the power factor angle of peak load and light load is generally considered as equal.

$$R = \frac{V_{PEAK} - V_{LIGHT}}{\sqrt{3}(I_{PEAK} - I_{LIGHT})} \cos\theta \tag{5}$$

$$X = \frac{V_{PEAK} - V_{LIGHT}}{\sqrt{3}(I_{PEAK} - I_{LIGHT})} \sin\theta \tag{6}$$

2.4 OLTC operation in series

There are multiple voltage levels used for generation, transmission and distribution in electrical power networks. In each area, OLTC transformer will be used between these different voltage levels as shown in Figure 8.

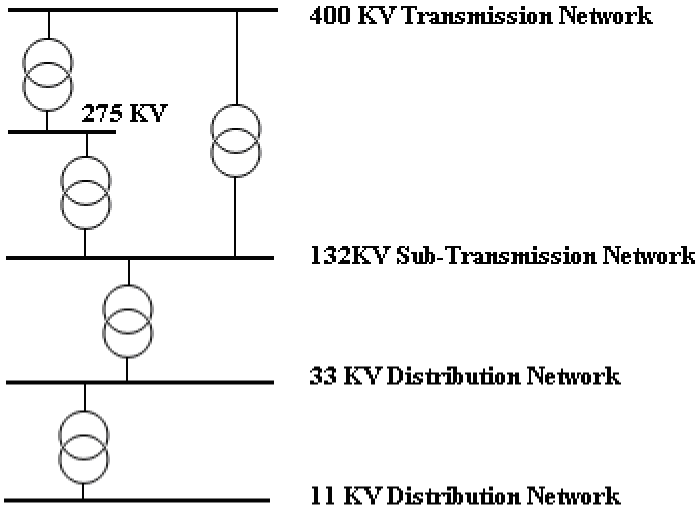


Figure 8. Different OLTCs operated in series

Conventionally, the voltage deviation in distribution networks is most often caused by feeder load variations or disturbances in feeding transmission network. The voltage control of OLTC with AVC relay compensates the voltage deviation due to distribution load changing and maintains distribution system to be stable when there are disturbances in the feeding transmission networks. Since OLTC operation schemes at different voltage levels are uncoordinated between each other in distribution networks, the down-stream OLTCs could operate before the up-stream OLTC operation and result in an unstable system. When the voltage deviation is caused by disturbances in feeding transmission networks or load variations in upper voltage level feeders, the duty of responsibility of operation belongs to the up-stream OLTC to have the priority to operate before the down-stream OLTCs. If the down-stream OLTCs operate ahead of time, they may have to revert to changing tap position back to original position after operation of the up-stream OLTC that corrected the voltage deviation. The time of voltage out of that required is therefore longer than necessary. Because OLTC is mechanical device, the increased number of tap changing operation can result in the high maintenance cost and reduced life cycles of the OLTCs. To avoid the incoordination of the OLTCs in different voltage levels, the tap changer should be operated under situation that its tap changing is the only operation to restore the required voltage to ensure voltage disturbance period minimization whilst reduce device maintenance cost. Thus the highest priority normally resides in OLTC of the highest voltage level in distribution networks [34]. Grading time is used to delay the down-stream OLTCs.

2.4.1 Grading Time

Due to uncoordinated control schemes between up-stream and down-stream OLTC controller, distribution system can become unstable. In order to ensure that the operation priority of the up-stream OLTC is higher than that of the down-stream OLTC, a widely accepted method used to set a longer initial time delay for down-stream OLTC relays than for the up-stream OLTC relay [34]. The Grading Time (GT) is introduced as an additional delay to ensure up-stream OLTC has finished its operation before down-stream OLTC restores voltage level [29]. The GT is set as the worst case voltage correction time. When the voltage deviation is corrected by up-stream OLTC operation, down-stream tap changing actions have time to re-set the tap changer operation. If the voltage deviation still exists after up-stream OLTC operation, down-stream OLTC can operate to execute local voltage correction [34].

The distribution network model of 132/33kV and 33/11kV is simulated by Simulink of MATLAB® software [35] to investigate the grading time (GT) scheme shown in Figure 9. The system parameters were: 132 kV generator of 100MVA capacity, 132/33kV OLTC transformer T_1 with 40MVA apparent power and nominal voltage of bus B_1 is 33kV. The apparent power for 33/11kV OLTC transformers T_2 and T_3 is 8MVA. The nominal voltage of bus B_4 and B_5 is 11kV and all OLTCs are all located on the secondary winding. The nominal voltage is 11kV of load 1 and 2 with 5MW active power and 1Mvar reactive power with a lagging power factor of 0.98 pu. The OLTC tap position range for all OLTCs is ±8, the reference voltage for OLTC transformers are all set to 1.0 pu, and the deadband setting is 0.03 pu.

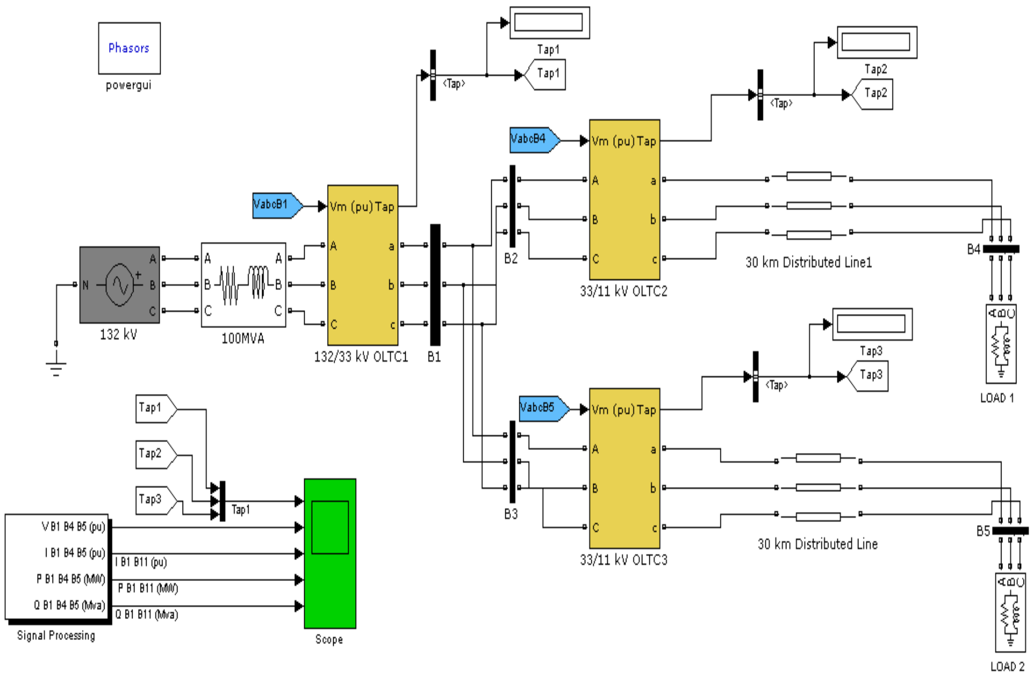
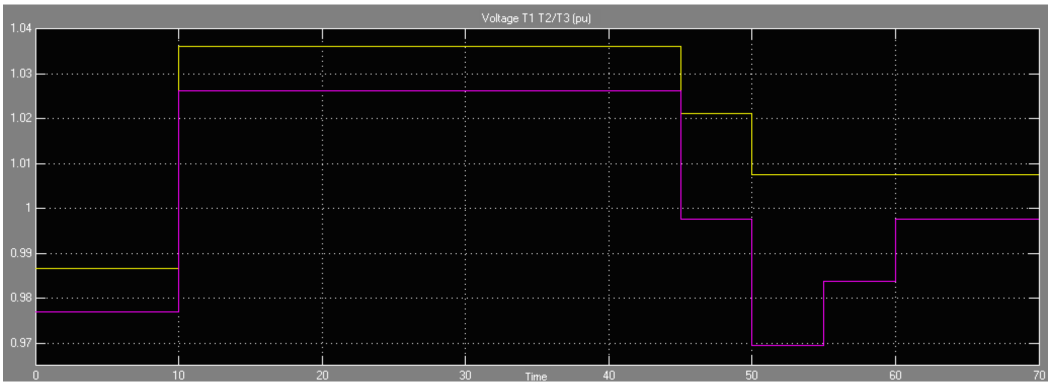
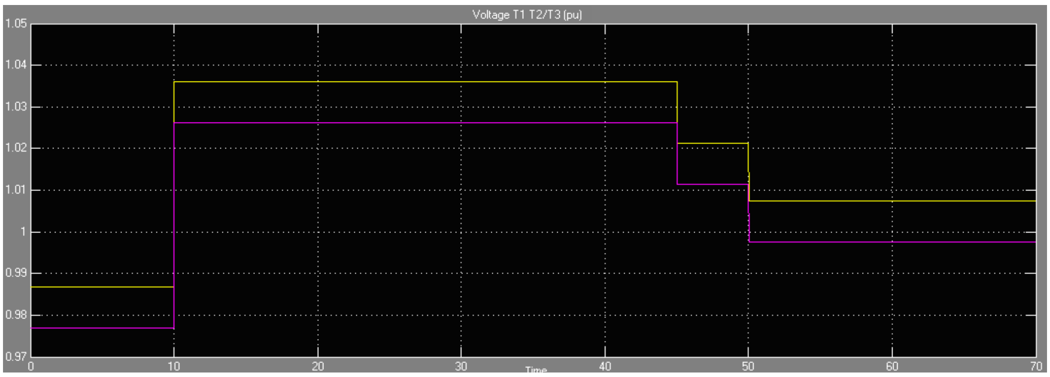


Figure 9. Simulation of GT scheme

The transient time of OLTC T_1 was set to 30 seconds as initial time delay for the up-stream OLTC to operate after voltage deviation. The grading time for down-stream OLTC was set to 60 seconds which enable the up-stream OLTC to complete the voltage correction. The operation time per tap changing is 5 seconds. The Simulink timing results of GT scheme are illustrated in Figure 10. The plot with yellow colour is the voltage profile for up-stream transformer T_1 and the plot with purple colour is the voltage profile for down-stream transformer T_2 and T_3. In each of the waveforms, the y-axis represents the per unit voltage and the x-axis the time in seconds.



(a)



(b)

Figure 10. Simulation results of OLTC voltage:
(a) Without GT scheme; (b) GT scheme

From Figure 10 (a) it can been seen that when the OLTCs are not using GT scheme, the total number of tap changing is 10 and the recovery time is 50 seconds when 132kV is changed from 1.0 pu to 1.05 pu at 10s. After 30 seconds transient time, the tap changers of OLTC transformer T_2 and T_3 (purple line) tap down 2 positions meanwhile OLTC transformer T_1 (yellow line) taps down 2 positions. After OLTC T_1 operation at 50s, OLTC T_2 and T_3 tap up and back to the original position. The recovery time is 50 seconds from voltage deviation at 10s to load voltage correction at 60s. In GT scheme as shown in Figure 10 (b), the delay time of OLTC T_2 and T_3 are 30 seconds longer than OLTC T_1. When 132kV is changed at 10s, only OLTC T_1 is operated after 30 seconds transient time and at 50s the voltage is restored to required level. After 60 seconds grading time, the operation of OLTC T_2 and T_3 are cancelled since the voltage deviation is corrected by the up-stream OLTC. With grading time applied, the total number of tap changing is reduced from 10 to 2 and the recovery time is reduced to 40 seconds due to the unnecessary operation of down-stream OLTCs was cancelled. The results of the simulation are listed in Table 1.

Table 1. Results of the GT scheme simulation

	Without GT scheme		GT scheme	
	Total tap changing number	Recovery time	Total tap changing number	Recovery time
132kV 5% changed	10	50 seconds	2	40 seconds

2.4.2 Communication assisted voltage control scheme

Since GT scheme uses the worst case voltage correction time as the time delay difference between different voltage levels, there are some advanced control methods to reduce the grading time in GT scheme.

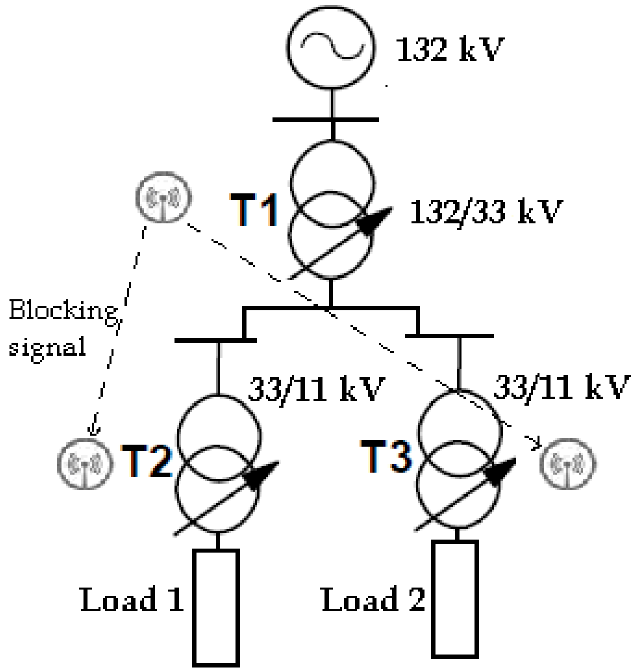
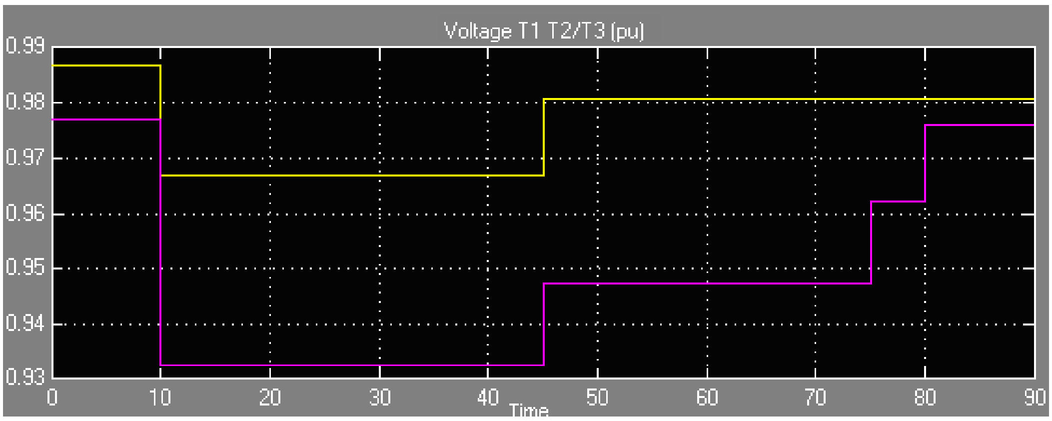


Figure 11. Communication assisted voltage control scheme

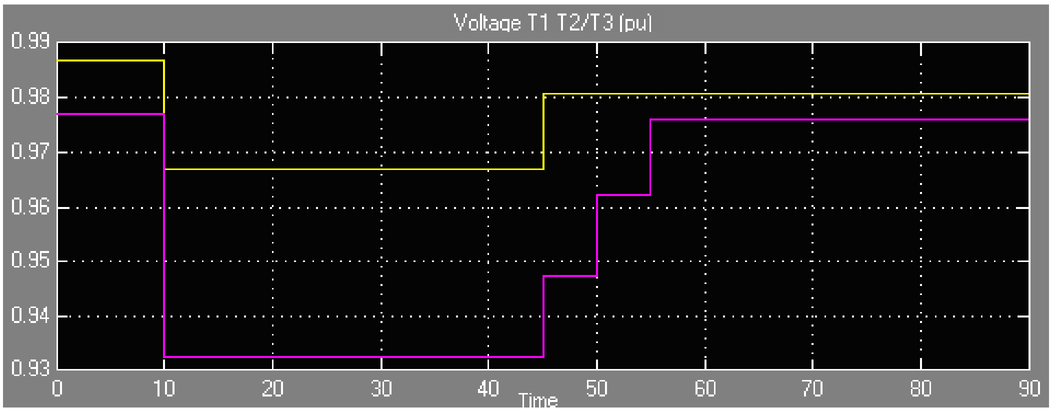
In a communication assisted voltage control scheme, a communication unit can be used to replace the need for GT delay between OLTCs at different voltage levels. When up-stream OLTC starts the operation, a blocking signal is issued to stop the operation of down-stream OLTC transformers as shown in Figure 11. The blocking signal is removed when the up-stream transformer has completed voltage correction. The down–stream OLTC can make further local voltage correction. Hence, time delay is reduced from the worst case correction time to up-stream operation time in communication assisted voltage control scheme [34].

The simulation results of communication assisted voltage control scheme compared with conventional GT scheme are shown in Figure 12 and 13. Figure 12 shows the results when there is a 5% change of load voltage and Figure 13 presents the results of 5% load voltage changed with 5% source voltage changed condition. The voltage is changed from 0.99 pu to 0.93 pu at 10s. The plot with yellow colour is the voltage profile for up-stream transformer T_1 and the plot with purple colour is the voltage profile for down-stream transformer T_2 and T_3. In each of the waveforms, the y-axis represents the per unit voltage and the x-axis the time in seconds.

From Figure 12 (a) and Figure 13 (a), it can be seen that the down-stream OLTCs T_2 and T_3 operated at 70s after 60 seconds grading time in conventional GT scheme and the recovery time is 70 seconds from 10s to 80s. In communication assisted voltage control scheme as shown in Figure 12 (b) and Figure 13 (b), down-stream T_2 and T_3 are operated immediately when the up-stream T_1 has completed its operation therefore the recovery time is reduced.



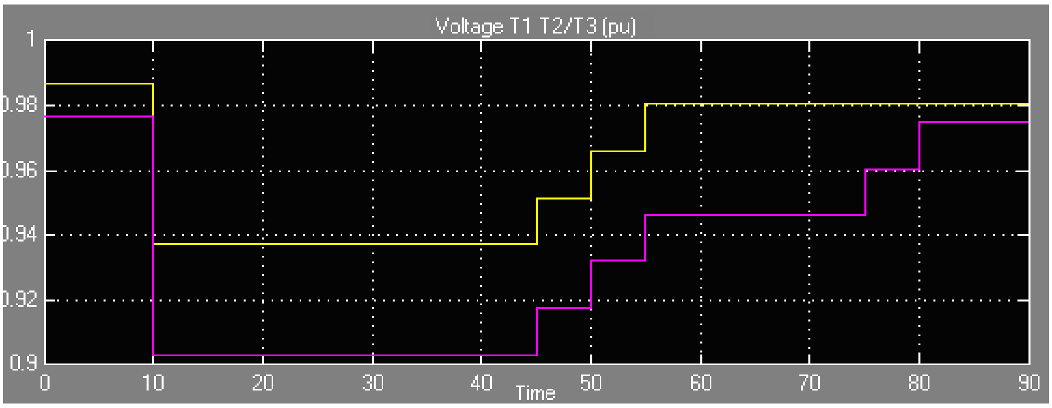
(a)



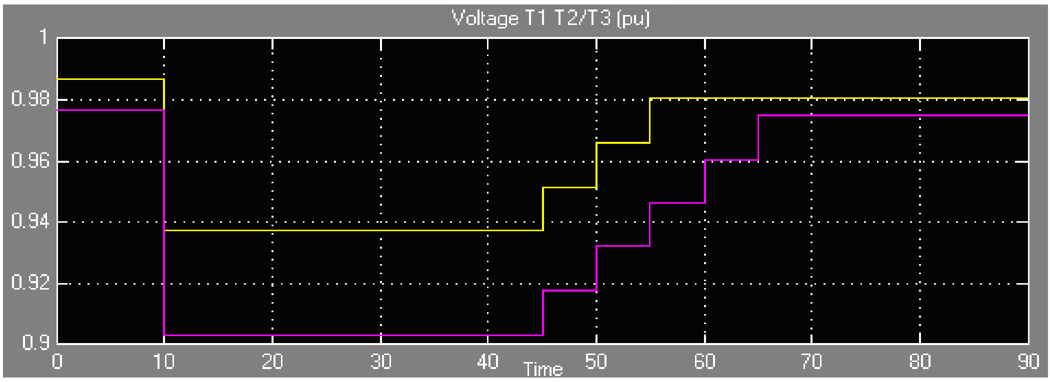
(b)

Figure 12. Simulation results of 5% load voltage changed:

(a) GT scheme; (b) Communication assisted scheme



(a)



(b)

Figure 13. Simulation results of 5% source voltage and 5% load voltage changed: (a) GT scheme; (b) Communication assisted scheme

Table 2 lists that recovery time of communication assisted control scheme at different voltage levels are reduced and maintain the quality.

Table 2. Results of communication scheme simulation

	GT scheme		Communications scheme	
	Total tap changing number	Recovery time	Total tap changing number	Recovery time
132kV 5% changed	2	40 seconds	2	40 seconds
Load voltage 5% changed	3	70 seconds	3	45 seconds
132kV 5% changed and load voltage 5% changed	5	70 seconds	5	55 seconds

Because of high cost of communications assisted voltage control schemes, the Enhanced Voltage Control AVC Relay Scheme defined in this research provides an autonomous tap changer control without the communications unit. This scheme includes the features of Source Drop Compensation (SDC) and Pre-emptive Tap Changer operation [34, 36].

2.4.3 Source Drop Compensation and Pre-emptive tap changing

Source Drop Compensation (SDC) determines the voltage at a regulation point by monitoring the source current and the feeder impedance between up-stream and down-stream transformer. The down-stream AVC relay gains an insight into this voltage when a voltage disturbance occurs. When the voltage at regulation point is within its deadband, the up-stream transformer operation is assumed to be complete and the down-stream AVC relay can proceed with local voltage correction. However, if the voltage of regulation point is without its deadband, the down-stream AVC relay will wait until the voltage correction of up-stream transformer completed [34].

Pre-emptive Tap Changer Operation is that when a voltage deviation occurs and the monitored voltage drop is changed with the disturbance, it can be assumed that the cause of voltage drop is either in full or in part done to a load change. Therefore, it allows the local AVC relay to correct voltage without waiting for any up-stream correction. The grading time delays can be over-ridden and a pre-emptive tap change initiated.

The enhanced voltage control scheme combining SDC and Pre-emptive Tap Changer algorithms and is simulated with the system in Figure 9 using Simulink of MATLAB®. The results are compared to those of the conventional GT scheme as listed in Table 3.

Table 3. Results of enhanced scheme

	GT scheme		Enhanced scheme	
	Total tap changing number	Recovery time	Total tap changing number	Recovery time
132kV 5% changed	2	40 seconds	2	40 seconds
Load voltage 5% changed	3	70 seconds	3	40 seconds
132kV 5% changed and load voltage 5% changed	5	70 seconds	4	50 seconds

C. Smith and M. Redfern have done a series of tests conducted to demonstrate the operation of the methods using a commercial Real Time Digital Simulator (RTDS) and commercially available AVC relay in the paper [36].

2.5 OLTC operation in parallel

With the growing customer demand for higher security and reliability of supply, it is common practice for DNOs to parallel transformers on one site in case one of transformers in the group is damaged or across the network to share overall load according to individual ratings of each transformer in order to meet the engineering recommendation as shown in Figure 14. Isolators are included to isolate one of the transformers when its maintenance is needed. A series of standard size transformer are suggested to be used as widely as possible when the OLTC transformers are operated in parallel.

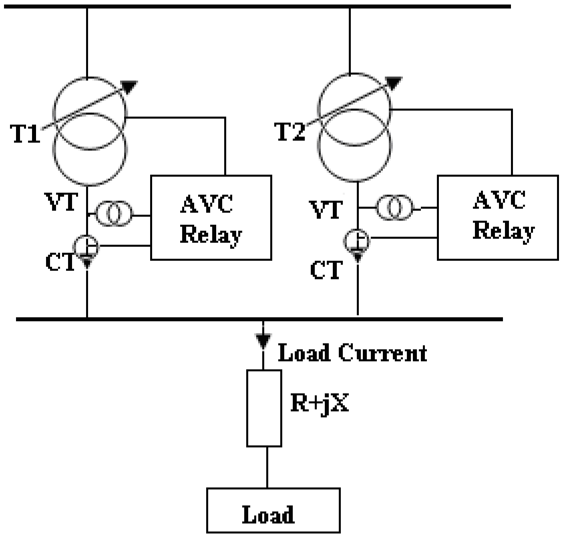


Figure 14. OLTCs operated in parallel

In this situation, the main aim of AVC scheme is to maintain the voltage within statutory limits, at the same time, to minimise the circulating current between parallel transformers. The OLTCs of paralleled transformers are necessary to have corresponding tap positions in order to achieve circulating current minimization [26]. The mismatch tap positions of OLTC transformers in one parallel group can result in reactive circulating current increasing between the mismatch transformers as part of transformer loading therefore the available capacity is reduced to supply consumers. Also the limit temperature that the transformer can tolerate may be achieved by the copper losses due to the increasing circulating current. The runaway situation must be always avoided when OLTC transformers are operated in parallel. Runaway are those tapping in the OLTC which causes them to run to their opposite position limits. Without effective control method, one tap changer always tap up when the voltage is low and the other tap changer always tap down when voltage is high. Since normally load varied throughout the day, runaway occurs when the maximum range of tap position is reached. The voltage control is lost when runaway happened and the extremely high circulating currents can result in damage of transformers [21]. The increased maintenance cost due to unnecessary frequent operation of tap changers is another motivation for the development of voltage control schemes to accomplish OLTC transformer operation in parallel. There are some basic voltage control schemes for OLTC operated in parallel as follows.

2.5.1 Master-Follower

A simple and extensively used AVC scheme is master-follower scheme. One OLTC transformer is designated as “Master” and all other OLTC transformers in parallel with it are designated as “Followers”. In this scheme the master transformer monitors required voltage and alters tap position to regulate voltage to desirable level. The other OLTC transformers replicate the same actions to keep all paralleled transformers on the same tap position as all OLTCs are wired together to enable tap changing signal to be disseminated [37]. The Master-Follower scheme can be used with LDC and operates under varying power factor, reverse power flow and DG integration. However, the disadvantage of this scheme is that the circulating current could flow between transformers if the paralleled transformers are not the same type and which tap positions of different transformer types are needed to be carefully decided. Additionally, parallel transformers must be on the same substation. It is impractical to use this scheme across a network due to the use of pilot line as connection between the AVC relays [37].

2.5.2 True Circulating Current

The True Circulating Current scheme is considered to use essentially identical transformers as Master-Follower scheme. This scheme regulates voltage as well as reduces circulating current between paralleled transformers. The use of different tap positions for different transformers will result in a circulating current I_C. This current is calculated by the interconnection between controllers to create a voltage bias V_{bias}. The biasing in opposite polarities is used as input to the AVC relays to correct OLTC reference voltage setting therefore the circulating current is minimised by the appropriate tap changing operation [37].

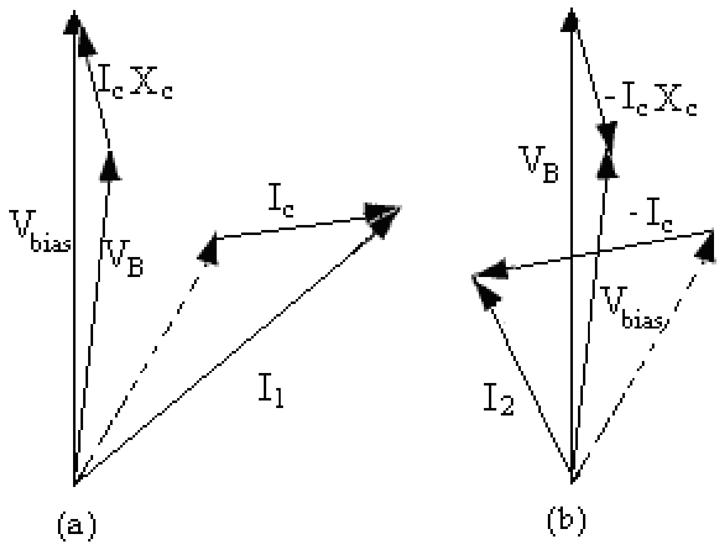


Figure 15. True circulating current principle:

(a) Transformer on higher tap; (b) Transformer on lower tap [21]

Figure 15 shows that the voltage bias calculated by circulating current is increased when tap position is high so AVC relay issues a tap down command and vice versa.

It can operate under a varying power factor, reverse power flow and DG integration. The challenge is that it is difficult to parallel transformers which are not in the same site. Communications between paralleled transformers is required since the current of all paralleled transformers must be available to the AVC relays to calculate the circulating current. However, LDC is affected by the large power output from DG even though this method is not compromised with a varying power factor [37].

2.5.3 Negative Reactance Compounding

The Negative Reactance Compounding (NRC) method is one of the common AVC schemes used for OLTC paralleling in distribution networks. The negative value of reactance with LDC settings is used to develop a voltage bias proportional to the current through the transformer and make the tap positions of paralleled OLTC transformers to be similar [38].

The following equations (7) (8) show the relationship between LDC settings and NRC setting:

$$Z_{LDC} = R_{LDC} + jX_{LDC} \tag{7}$$

$$Z_{NRC} = R_{NRC} - jX_{NRC} \tag{8}$$

The Figure 16 illustrates the NRC principle. The tap position of transformer T_1 is higher than that of transformer T_2 in this situation. A circulating current occurs and flows between two paralleled transformers. The individual transformer current I_{T1} is shifted clockwise and current I_{T2} anti-clockwise by circulating current. A voltage drop $I_T \cdot Z_{NRC}$ is created to modify reference voltage from V_{AVC1} to V_{VT} and used by the AVC relay to correct tap position. The effective measured voltage V_{AVC1} is seen by AVC relay of T_1 higher than modified target voltage V_{VT} and as a result the tap change is down. A similar action is done by the AVC of T_2 but the tap change is up. When the circulating current is eliminated and reference voltage is achieved, the action stops and there is a similar tap position of both parallel transformers [37].

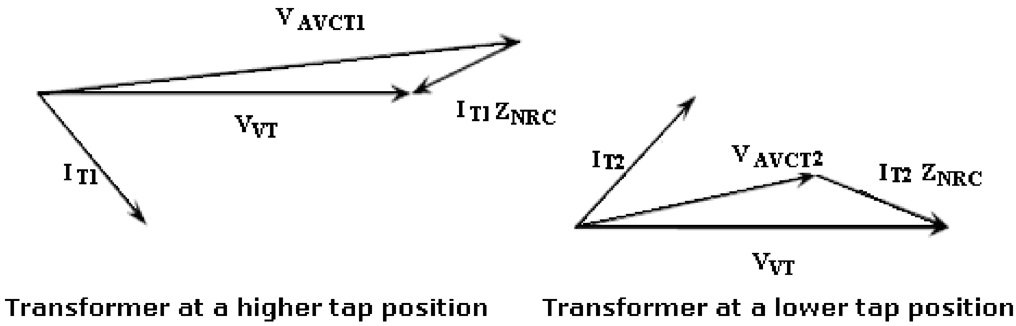


Figure 16. NRC principle [37]

The paralleling transformers with the NRC scheme can be operated with transformers at different positions in networks and it is unnecessary to be identical anymore due to independently action of each transformers. However, the NRC scheme is not accurate without unity power factor thus it is susceptible to varying power factor. The voltage error is increased due to power factor deviation [38]. The performance of LDC is reduced due to the negative value of X_{LDC} setting and an increased value of R_{LDC} is necessary to keep the same boost.

2.5.4 Transformer Automatic Paralleling Package, TAPP [37]

The Transformer Automatic Paralleling Package (TAPP) scheme, based on NRC scheme [38], reduces the circulating current between paralleled transformers by dividing measured current into load transformer current and circulating current as shown in Figure 17.

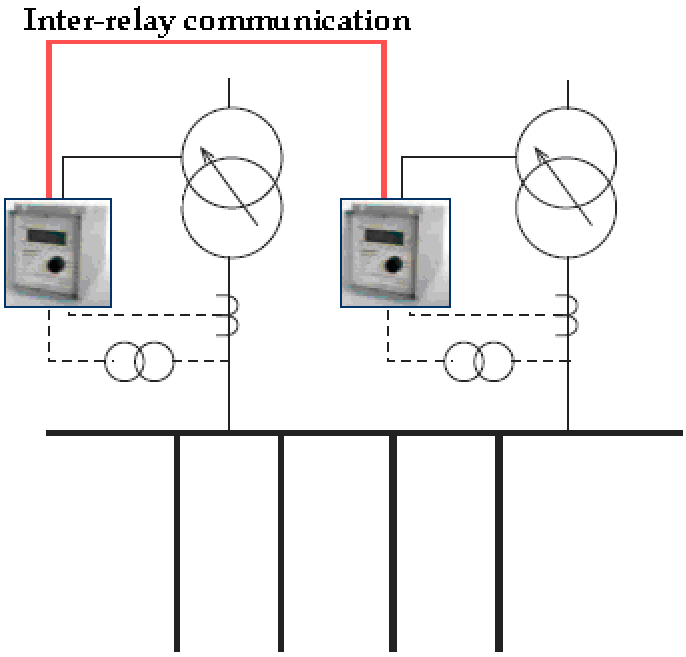


Figure 17. TAPP scheme [37]

TAPP scheme based on target power factor, to evaluate circulating current by comparing the measured transformer load current (I_{TR}) with the target power factor (pf_{target}) as shown in Figure 18. Two separate circuits, one for LDC and one for compounding, are introduced into TAPP scheme to eliminate LDC degradation with NRC. However, the disadvantage of TAPP scheme is that load power factor deviation will result in an error in the controlled voltage due to part of load current being considered as circulating current. The specified power factor is necessary to make voltage control to be satisfactory. The significant power factor deviation caused by DG results in the unsuitable of this scheme [37].

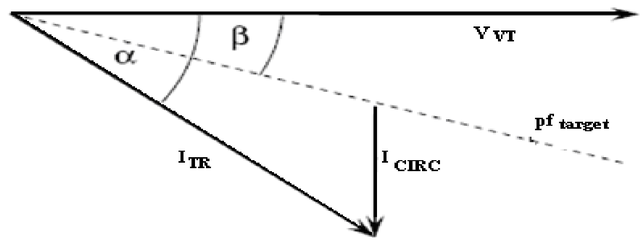


Figure 18. Principle of TAPP scheme [37]

The paralleling operation of OLTC transformers is supported by the above methods to provide higher security and reliability of power supply to customers. Since these methods are only designed to provide parallel operation of OLTC transformers in distribution networks, effective OLTC voltage control methods have also to be implemented to control the voltage within statutory limits under different network conditions.

2.6 Fuzzy logic based AVC control [39]

The OLTC voltage control with simpler and faster fuzzy-logic based AVC relay has advantages that the fuzzy logic uses simple "IF-THEN" relations to make its representation very clear and be easy to understand [40]. Hence, the design is less complex with an improved control performance as well as a less hardware costs. Figure 19 shows the basic diagram of fuzzy logic based AVC relay [39].

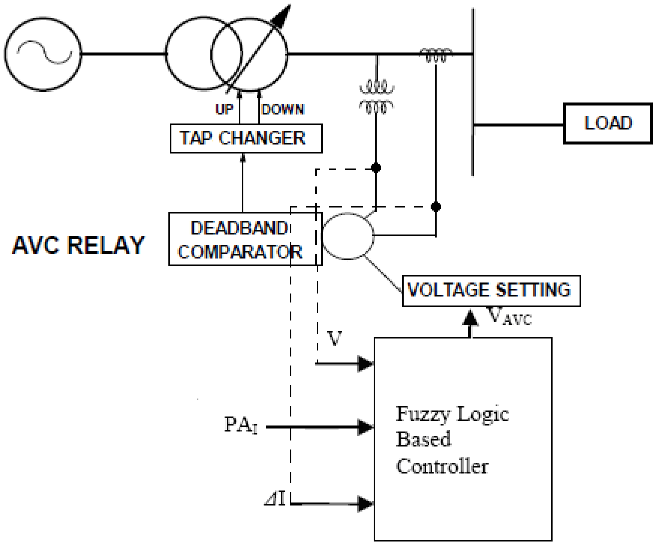


Figure 19. Fuzzy logic based AVC relay

The membership of input and output signals

Secondary voltage of OLTC transformer (V): high (H), normal (N), low (L)

Phase angle of transformer current (P_{AI}): high (H), normal (N), low (L).

Change of current (ΔI): negative (N), zero (Z), positive (P)

AVC relay voltage (V_{AVC}): high (H), normal (N), low (L).

The control rules

Load increasing (current change is P)

If voltage is L, then output is L.

If voltage is N and phase angle is L, then output is L.

If voltage is N and phase angle is N, then output is N.

If voltage is N and phase angle is H, then output is N.

Load decreasing (current change is N)

If voltage is H, then output is H.

If voltage is N and phase angle is H, then output is H.

If voltage is N and phase angle is N, then output is N.

If voltage is N and phase angle is L, then output is N.

The output V_{AVC} is provided to the AVC relay as reference voltage. When the output V_{AVC} is low the OLTC taps up and taps down if output V_{AVC} is high. S. Salman and Z. Wan present the detailed simulation results of this control method in the paper [39, 41].

2.7 Time-interval based voltage control strategy [42]

The time-interval control strategy is an off-line OLTC setting control approach to dispatch OLTC operation based on a predetermined setting point for OLTC by a one-day-ahead load forecast without communication systems between equipments.

The next day load is divided into different load levels that the load profile is estimated due to certain load pattern during next day caused by everyday social activities with a value of less than 2% as the average forecasting error one-day-ahead [43]. The setting point of OLTC is maintained unchanged during each load level, but OLTC tap setting can occur between different load levels therefore the total number of tap changing is reduced [42].

Z. Hu, *et al.* present the detail simulation results in [42] indicate that the time-interval based voltage control for reference voltage setting point of OLTC is simple and effective when the one-day-ahead load forecast is accuracy and the voltage at the primary busbar of substation is constant. The voltage quality is improved and power loss is reduced significantly.

2.8 Other voltage control methods in distribution networks

Besides OLTC transformer, there are some other devices and approaches currently used for voltage control in distribution networks. These methods have different roles and impacts depending on level of voltage and network type.

2.8.1 Reactive power compensation

In transmission networks, shunt capacitors or reactors are commonly used to import or export reactive power in some nodes to maintain the voltage as a regulation device. In distribution networks, a capacitor bank can be connected in parallel across feeder line and automatically switched to increase voltage by the use of reactive power depending on node voltage degradation [24].

The efficiency of reactive power compensation for voltage control in distribution network is highly depending on the X/R ratio of distribution lines. A lower X/R ratio of distribution network results in the use of reactive power less effective for voltage control as shown in equation (9)

$$\Delta V = V_1 - V_2 \approx \frac{RP_L + X(Q_L - Q_C)}{V_2} \tag{9}$$

where ΔV is voltage drop between substation sending-end and capacitor connection point, R, X is line impedance, P_L, Q_L is active and reactive power of load, Q_C is the reactive power of capacitor.

Therefore the number of these Var compensation devices installed in distribution networks is very small and the cost of reactive power compensation for voltage control is expensive. Another limitation of reactive power voltage control is the network losses are increased since the line current is increased caused by the reactive power.

2.8.2 In-line voltage regulator

Along a long 11kV feeder line, a voltage regulator can be installed into the long circuit to divide it into two sections. The in-line voltage regulator provides an additional voltage control point for the lower section which has excessive voltage drop [24]. There is only a few number of in-line voltage regulators installed in the UK at present and these devices are not commonly and costly.

2.8.3 Network reinforcement

One of passive solutions to improve the voltage profile of distribution network is network reinforcement. The resistance and reactance of feeder are reduced in order to upgrade the conductor size to smooth voltage profile. This method increases the availability, improves power quality and reduces losses. However, implementation of this solution is associated with significantly high costs and causes disruptions.

Chapter 3

Overview of distributed generation technologies

This chapter investigates different DG technologies with consideration for their output power characteristics. The techniques and challenges of different DG are briefly introduced.

3.1 Introduction

For more than 120 years, electrical power has been generated in centralized large power station, such as fossil fuel, nuclear or hydropower plants which are specifically located either close to sources of fuel, primarily coal or far from concentration of load centres in the case of nuclear. Since the scale of these plants is large with excellent economics, the ever larger power plans had been built to benefit from the economy of scale until 1990s. However, the long distances to transmit electricity from power plants to end customers and the negative influence to environment cannot be ignored [44].

Due to the low carbon energy policy from government, the use of small scale generations that are connected in local distribution networks rather than transmission networks, referred by the term "Distributed

Generation" (DG) is attracting more and more attention. The fundamental benefit of DG is that it changes the conventional generation-transmission-distribution structure where electricity power is transferred over long distance from generation to end users, significantly reduces transportation cost and saves power loss due to line impedance. The technologies using renewable resources generate power to supply local load in order to solve network constrains and reduce carbon emission as well are the main drivers to encourage growth of DG.

It is not necessarily correct that DG is only related with generation of power from renewable resources since there are a number of DG technologies based on various primary energy resources including conventional fossil fuel. Nevertheless, DG is close associated with renewable technologies since the generation using renewable energy resources normally has small scale and the number of renewable DG is continuing to grow due to government's ambitious carbon emission reduction plan. Additional, environmentally friendly power supply technologies of DG can ensure that DG location close to urban areas with concentrated load centres [45].

DG technologies are normally classified into two main categories as conventional or renewable based on the type of primary energy resource. The conventional DG includes Internal Combustion Engine (ICE), cogeneration, micro-generation, fuel cell etc. Solar photovoltaic, wind generator, biomass, small hydro power plant, geothermal heat pump, tidal and wave power generation are considered to be renewable DG.

From the output power control point of view, DG can be classified based on generation output characteristic as dispatchable DG or non-dispatchable DG. The output characteristic mainly depends on primary energy resource. Dispatchable DG refers to primary energy resources that can be supplied under DNOs' request in order to control the output power to required demand value [46]. When the energy resources of electricity cannot be dispatched by network operators, the DG is non-dispatchable where output power is impacted by the intermittent nature of primary energy resources particularly renewable energy resources.

The electrical machines like synchronous or asynchronous generators are used as the main equipments in DG technologies with direct connection or power electronic technique interface to distribution networks [47-49]. The DG technologies of ICE, cogeneration, biomass, solar thermal and geothermal generally employ synchronous generators as power generator to produce electricity and control reactive power. The asynchronous generator is extensively utilized for DG with wind farms and small hydropower plants. The power electronic device interfaces DG with networks is used in solar photovoltaic system, fuel cell and wind power plant with controllable reactive power output.

3.2 Internal Combustion Engines

Internal Combustion Engine (ICE) dates back to the middle of 19th century as fundamental prime mover in DG system. The fuel combustion occurs in a confined space of ICE to produce hot expanding gases that are concentrated to drive the generator directly.

The proven technology history, wide industry penetration and the ease of maintenance make ICE to be one of the most common DG technologies. The low device cost of ICE is achieved after the long history development and ICE can be installed in more space limited locations since the size is generally smaller than other DG. The large scale range of ICE is available from 1kW to more than 30MW with good efficiency and operating reliability [50].

However, the high NO_X and SO_X emission and noise by ICE results in a significant environmental and noise pollution, especially compared to the other renewable DG technologies. Though the current efficiency of ICE can reach near 40%, high fuel costs are the main barriers to ICE implementation as DG [13, 51].

3.3 Cogeneration

Cogeneration, sometimes known as Combined Heat and Power (CHP), is the most significant DG type at present. CHP generates both electricity and heat, beneficially using the waste heat from energy conversion process simultaneously for industrial processes or alternatively is transported to local communities for district heating [52].

The best CHP schemes can achieve a fuel conversion efficiency of 90% and the overall efficiency of nearly 70% ensures that the CHP has the significant potential to reduce environmental impacts as well as good economics. Since the last article was published in the Digest of United Kingdom Energy Statistics (DUKES) on 26 July 2012, the Good Quality CHP capacity in the UK has increased by 1 per cent from 6,053MW to 6,111MW between 2010 to 2011 [53]. There are many forms of technology used in CHP from 1kWe to 100s of MWe such as gas engines, gas turbines, combined cycle gas turbines, diesel engines etc. [52]. Two major factors impact economics of CHP are the cost of fuel (principally natural gas in the UK) and electricity generation efficiency. Conventionally, the location of CHP is fixed by position of the heat load and the output power is controlled to meet the heat energy demands of host site.

A range of developed technologies like Fuel Cell with higher power efficiency and Stirling engines are supporting CHP for individual homes as Micro-CHP that are below 1MW and connected to the LV or 11kV distribution networks [54]. The renewable resources used for CHP means that CHP will improve efficiency and lower environmental impact to play a more important role as DG in the UK and worldwide. The development of CHP is considered in the Energy Review of 2006 and Energy White Paper of 2007 of UK government [55, 56].

3.4 Micro-generation

The micro-generation defines a range of generation technologies that electrical power is generated at domestic scale for local consumption. The most common micro-turbine uses small scale gas turbine technology that is originally designed for mobile transportation. It is also used in electrical power generation as DG technology for the domestic area now. Micro-turbines commenced field test around 1997 and were initial commercial used in 2000 [57].

The available and developing size range of an individual micro-turbine unit is from 30 to 350kW which can be used in power-only generation or CHP plants. Micro-turbines run at extremely high rotational speed about 96,000 revolutions per minute (rpm) in the case of a 30kW unit and one 45kW model on the market turns at 116,000rpm [58]. A high frequency AC (Alternating Current) output power is generated by the high speed generator (about 1,600Hz for a 30kW machine) and employs power electronic devices to rectify the power to DC (Direct Current) and then invert to 50Hz for the UK grid connection.

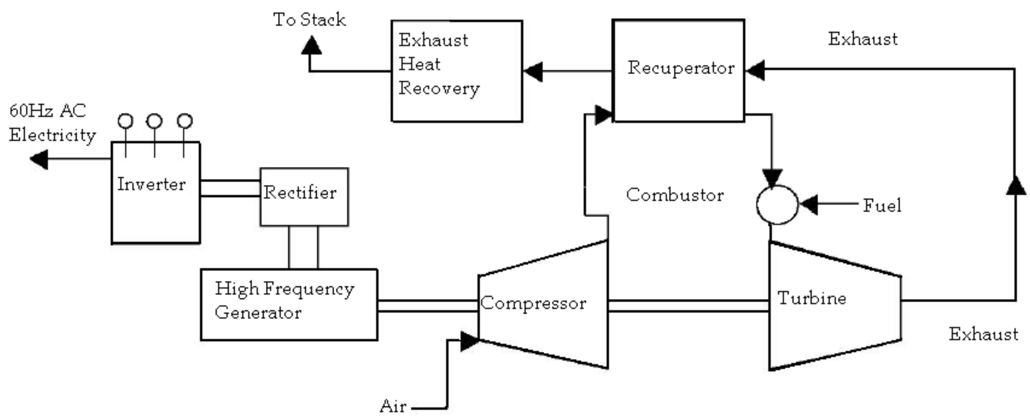


Figure 20. Micro-turbine CHP system [57]

The power efficiency of micro-turbines is about 30% for power-only generation and the 85% can be achieved to combine with CHP plants as shown in Figure 20. An extremely low NO_X emission can be ensured due to low combustion temperature of micro-turbines [59]. And the potential use of renewable resource as fuel of micro-generation promises future opportunity of commercial micro-wind turbine, micro-CHP and fuel-cell CHP. However, high cost is the main barrier for commercial reality. Since the number of micro-generation units in current commercial use is small, there is not sufficient information to obtain a forceful conclusion about the reliability of micro-generation.

3.5 Fuel Cell

The fuel cell is a very simple electro-chemical device which was invented in 1839 by Welsh Physicist William Grove. The chemical energy from a fuel is converted through the chemical reaction of reversed electrolysis process combining oxygen and hydrogen to produce electricity and heat power as shown in Figure 21. Sometimes natural gas and methanol are also used as the fuel [60]. The characteristics of fuel cell are quite different from conventional generations and batteries. The electrical power is converted directly from chemical energy without the thermal-mechanical procedure and electricity can be produced continually with an uninterrupted fuel and oxygen supply.

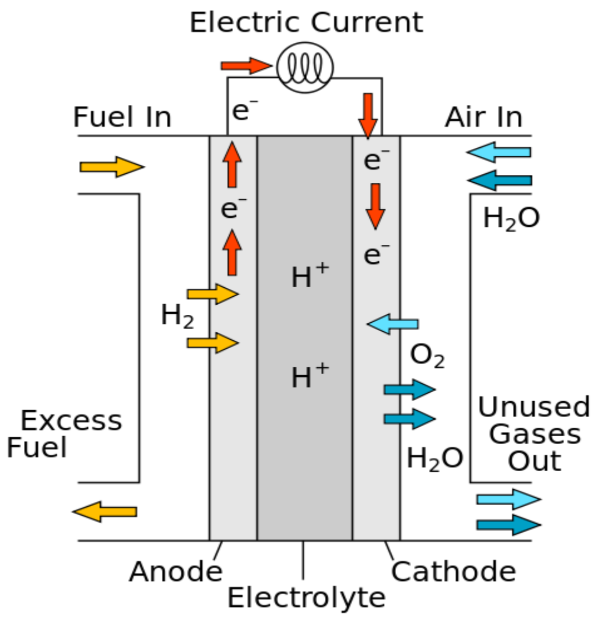


Figure 21. Scheme of a proton conducting fuel cell [60]

The fuel cells are classified by the electrolyte type using in generation process such as Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Polymer Electrolyte Membrane (PEM) and Solid Oxide Fuel Cell (SOFC). The normal range of the fuel cell size is from 1kW to 3MW according to different fuel cell types. The average voltage of single cell is 0.7V. The practical fuel cells place such single cells into 'stacks' to increase the voltage and provide the required voltage and power [60]. The power electronic DC/DC converter and DC/AC inverter are used to control fuel cells and achieve the grid connection.

The fuel cells generally have a high power efficiency to produce electricity at the range of 40% to 60%. If the waste heat from energy conversion is also used, 85% efficiency can be achieved with negligible NO_2 and other harmful emissions. The large range of available size and extremely low noise provide the opportunity to be installed near residential load centres. The primary constrains for development and commercialization of fuel cells is the high cost [61].

3.6 Solar Photovoltaic

Solar Photovoltaic (PV) refers that the energy from sunlight is directly converted into DC electricity using solar cells containing solar photovoltaic material that implement the photovoltaic effect. Solar panels composed of a number of solar cells are used in PV systems and DC/DC converter is employed to supply DC load or with DC/AC power inverter for AC load or at interface with distribution networks.

The capacity of PV is measured as the maximum output power under Standardized Test Conditions (STC) in Watts peak (Wp) [62]. This maximum value is used as the rated value and the actual power produced from PV at a particular time may be different according to many other factors such as weather, location and time [63]. The typical solar panel rating is ranged from below 100Wp to over 400Wp [64]. The PV array arranges a collection of solar panel in multiples to provide the desired voltage and power. The grid-connected PV systems may include a Maximum Power Tracker (MPT) control system, battery system with charger and DC/AC synchronizing inverter as Figure 22, there are various sizes ranging from 2kWp for residential consumers to solar PV plants up to 10s of MWp. And the power factor of PV is restricted to operate between unity power factor and 0.95 leading as DG technology [65].

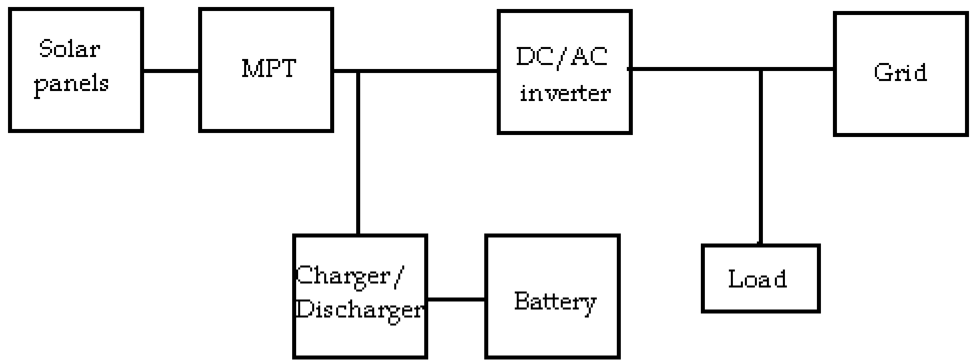


Figure 22. Basic grid-connected solar PV system

The technology of solar PV has developed rapidly over the last 20 years. The total installed capacity of PV is 67.4GW by the end of 2011 and the number is increased to 100GW by the end of 2012 [66].

Although PV is not fully economic competitive with conventional and popular renewable power generation, it still attract interest and is encouraged due to its environmentally friendly and unlimited energy source availability. Solar power is clean to be used with no emission and there is no noise when PV system is operated therefore it is the perfect DG technology to be used near the point of power demand while reducing transmission loss. The PV systems have a long life typically 25 years or more with easy maintenance and low operation cost compared with other existing DG technologies.

Though the operation cost of PV system is extremely low compared with other DG, the higher initial capital cost of installing PV plants and low capacity factors (generally under 25%) are the main barriers for PV systems [51]. The restricted requirement of PV installed area location is another factor to be considered. The diffuse and intermittent nature of solar energy is the main reason for low capacity factor of PV systems [67]. The high installation cost and low efficiency make solar PV systems much more expensive than the other generations and about 2 to 5 times the cost of gas generated power. However, the cost of PV has a good prospect for continued reduction as the photovoltaic material developed. Compared to other popular energy sources, the invested research funding is less in the improvement of solar PV systems. Thus the headroom of PV development has a large potential that the efficiency will raise while the cost of solar cell and relative production will be reduced [68].

3.7 Wind generation

Wind power is the conversion of kinetic energy from wind into a useful form of energy. The wind energy is converted into mechanical energy by using wind turbines and then the mechanical energy is used to drive generators to produce electrical power. Generally, a wind farm is a group of individual wind turbines contains several wind turbines in the same location for wind electricity generation.

It is in the last few decades that wind power has played an important role in electricity generation of renewable energy resource. The capacity of both off-shore and on-shore wind power farms are increasing significantly. Many large wind farms contain hundreds of wind turbines and are installed for commercial use. The size of individual wind turbine has increased significantly from tens of kW to be up to 7.58MW (Enercon E-126) 2011 [69]. There are a lot of MW scale wind farms ranging from a few MW to tens of MW to generate economical clean electrical power all over the world competing with conventional power plans using fossil fuel. These large-scale wind farms are often connected to high voltage levels of distribution networks or transmission networks as central generation rather than DG due to the economics of scale for wind power technology. Until recently, small-scale wind generator has meant that they all qualified as DG to be connected directly to lower voltage distribution networks.

There are several popular types of wind turbines being used in the practical wind farms such as wind turbine with Induction Generator (IG type), wind turbine with Doubly Fed Induction Generator (DFIG type) and wind turbine with Direct-Drive Permanent Magnet Generator (DDPMG type) that all have different characteristics. The IG type wind turbine was widely used in wind farms at the early stage of wind generation development. It is a fixed speed type with low efficiency that the maximum power of wind turbine is untracked. When a squirrel cage induction generator is used in IG type wind turbine as shown in Figure 23, the reactive power is absorbed by the generator from power grid and it significantly impacts on voltage stability of power network by the adverse operation characteristics [70].

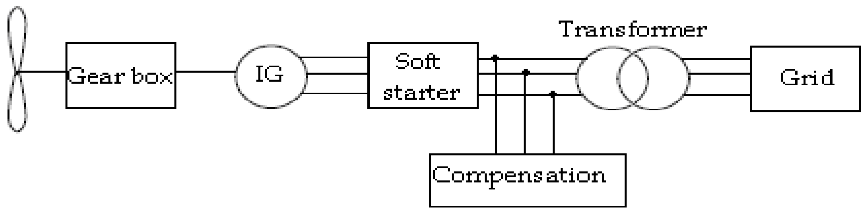


Figure 23. Wind turbine with squirrel cage induction generator

Recently, DFIG type wind turbines are developed and equipped very rapidly, especially in the past few years that most of installed wind turbines are DFIG type [70]. The DFIG type wind turbine is a variable speed type with an improved efficiency compared with IG type. The DFIG generator of wind turbine has windings on both its stator and rotator where a significant power is transferred between shaft and power grid. The stator winding of DFIG is directly connected to the three-phase power grid while the three-phase rotor winding is fed back from the stator through a rotating or static voltage source converter as shown in Figure 24. The back to back Insulated Gate Bipolar Transistor (IGBT) inverters are used in wind turbines up to MW scale today. The active power and reactive power of DFIG type wind turbines can be independently controlled flexible [71].

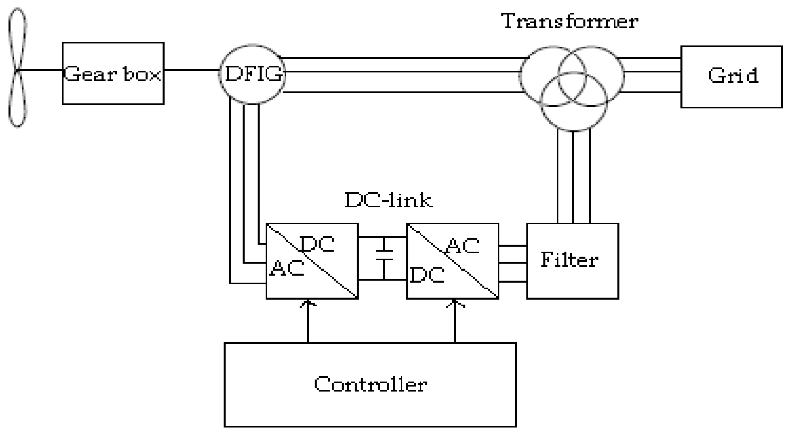


Figure 24. DFIG type wind turbine

The DDPMG type wind turbines have attracted interest due to developments of the permanent magnet generator. It is a full-variable-speed wind turbine with high efficiency especially when speed of wind turbine is low. The permanent magnet generator of wind turbine is directly driven without gearbox thus the maintenance cost of DDPMG type wind turbine is lower compared with other wind turbine types. The controller for generator is simple without excitation system due to the fact that the material of generator rotor is permanent magnet as shown in Figure 25. A full-scale frequency converter is required in DDPMG type wind turbine to interface with power grid therefore reduce the interaction between permanent magnet generator and power grid [72].

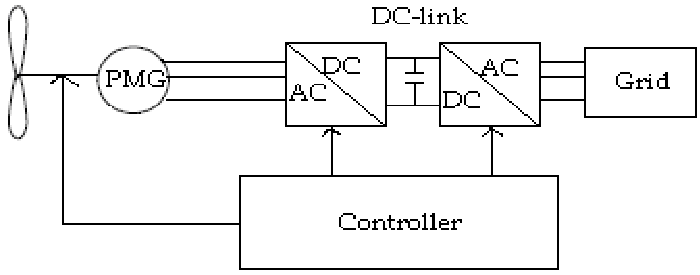


Figure 25. DDPMG type wind turbine

The wind generation technology presents many challenges to distribution networks as DG. The main challenge is intermittent nature of wind that results in the output power uncontrollable and grid reliability due to the different characteristics of wind turbines to conventional generators when connected to lower voltage distribution networks [73]. The output power from wind generation is non-dispatchable on demand due to the nature of renewable energy resources. The dispatcher can only constrain the generator's power factor. Since the close balance between supply and demand must be ensured by DNO, the penetration of wind turbines as DG connected to distribution networks is a major topic for research. However, it is possible for electricity generation to be benefit significantly from the contribution of wind generation as a clean and unlimited renewable energy resource.

3.8 Biomass

Biomass resource is biological material from organisms including crops, agricultural residues, animal manure, industry waste [74] etc. It can be used in the form of wet or dry fuel and then be combusted to generated electricity or heat. Co-firing is the current biomass electricity generation technique that biomass is used with coal in the existing power stations.

Due to the carbon-free combustion process that the captured emission is combusted by plants and the good efficiency of biomass co-firing, the use of biomass as renewable resources for electricity generation is expanding. The biomass plants for CHP are generally smaller size and the efficiency is increased from 20%-35% for coal plants to 85%-90% for cogeneration with available feedstock.

Global biomass electricity capacity is in the range of 47GW, with 2 to 3GW added in 2005. It is a slow process to adopt the biomass-based DG since energy density is low with high transportation cost of the basic fuel. The cost and low conversion efficiency is the main barriers of biomass to be widely commercial used and the feedstock availability is another constrain for biomass to be used near residential load as cost-effective DG technology [75].

3.9 Small hydro

Hydro power is the generation of electricity from flow and fall movement of water by hydropower turbines. The dependable flow of water from a reservoir is poured into turbines from a required height of fall of water. The shaft is rotated by water pressure and is converted into electricity by generators. Small hydro has been developed due to the liberalization of electricity market as small-scale powers supply that up to 10MW capacity for local community or industry [76]. The capacity of mini-hydro is usually defined as between 100kW to1MW and micro-hydro capacity is below 100kW for smaller communities use.

The environmental impact of small hydro power is much less than large hydro because of the smaller size of reservoirs and install construction. The small hydro power is a renewable energy with low cost and low environmental impact to be connected to distribution networks. The small hydro power capacity in Europe is 13GW in 2006 [77] and during 2008 it grows by 28% from 2005 to raise the small hydro power capacity to over 80GW all over the world.

However, the small hydro power is constrained by location limits. Some isolated area near lake or river may be uneconomic to serve from distribution networks or even no distribution networks.

3.10 Summary

The generation scale of DG is small and is connected to distribution networks. When the size of above DG technologies is used in large scale or connected to transmission networks, the technology is no longer considered as DG. The DG capacity has grown from 1.2GW to over 12GW in England and Wales during the last two decades [44, 78]. The economics of competitive DG technologies will result in the further growth of DG capacity. A range of different DG technologies have been developed driven by higher fossil fuel cost and limited availability, emission reduction target of government and economical of renewable energy resources. Since the wide range of DG technologies is being developed and connected at different voltage levels of distribution networks, a number of new challenges have been presented in power systems. A high penetration level of DG (more than 20%) with different capacity and locations connected to distribution networks can impact on the operation, control, reliability of distribution networks significantly [79-81]. These issues must be critically assessed and resolved before DG is allowed to participate into electricity networks [19]. How DG can impact on OLTC voltage control in distribution networks is explored in further detail.

Chapter 4

Future voltage control in Smart Grid using Smart Meters

This chapter briefly introduces the concepts of Smart Grid and the intelligent functions of the Smart Meter. Different voltage control approaches with different communication technologies and Smart Meters are reviewed. The latency of an example solution for voltage control using Smart Meters in the UK is used in order to demonstrate the possibility of real-time voltage control in Smart Grid with existing communication technologies.

4.1 Introduction

Electricity is one of the most important elements for society and industry. However, the traditional power grid was built many decades ago and has been difficult to support the required changes such as high DG penetration, growing load demand and low carbon emission target. The amount of fossil fuel resources is being reduced thus the cost of fossil fuel is increasing significantly and oil price is volatile when social and political factors are considered. Therefore many governments have plans to reduce the dependency on oil and gas [82]. Renewable energy is attracting more and more attention to meet the target of governments for CO_2 reduction. With more renewable generators connected to distribution networks, the traditional power networks have many challenges that need to be addressed. Since the cost of capital investment for whole network reinforcement is extremely expensive, a more efficient and reliable power grid, a “Smart Grid” has emerged to address these challenges based on the existing power networks.

There is no a universal definition for Smart Grid. Different countries have different definitions due to their own requirement for Smart Grids. Generally, Smart Grid is an electrical distribution network being transitioned from a traditional passive one into an intelligent active network which can accommodate high levels of renewable DG penetration to improve the performance and flexibility of network operation by communication technologies. This revolutionary transformation requires the installation of advanced intelligent equipments in existing networks. This includes the use of digital Smart Meters [83] to replace the traditional electro-mechanical meters. Two-way communication functions, embedded as part of Smart Metering technology, will provide the potential opportunity to achieve real-time measurement and control of distribution networks. Typical communication technologies have been investigated to demonstrate the availability of smart real-time voltage control in short-term or medium-term practice.

4.2 Concept of Smart Grid and Smart Meter

The term “Smart Grid” is generally used to represent the integration of all supply, grid, and demand elements connected to a digital power grid with a reliable, resilient, secure, and manageable standards-based open information infrastructure which can provide two-way communications to offer numerous benefits for both power suppliers and consumers [84]. Figure 26 shows the general structure of a Smart Grid.

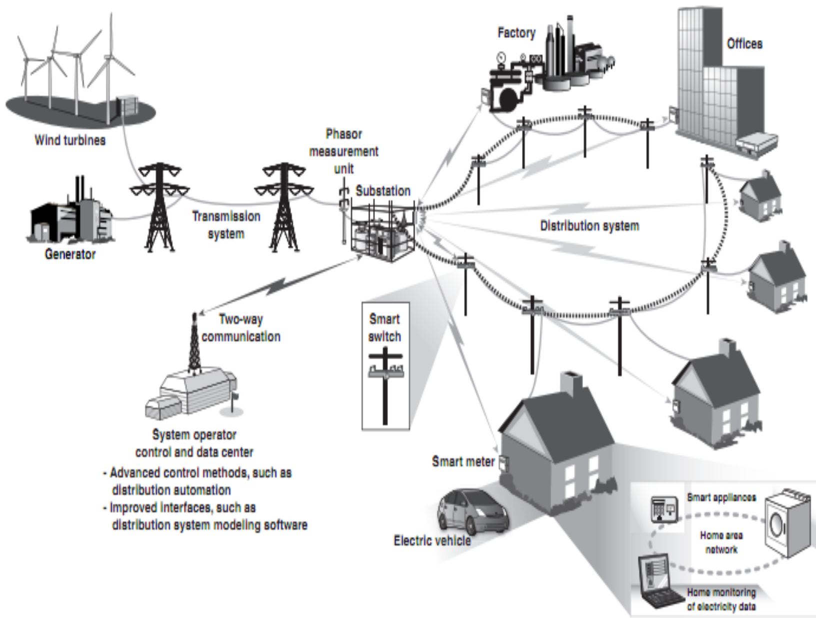


Figure 26. Structure of Smart Grid [85]

Although the details of Smart Grid have not been definitely determined, the functions should involve self-healing, integration, optimization etc. Smart Grid can assess its health in real-time, accommodate new environments, control distributed resource integrations and optimize the response to end user demands [86]. The Smart Grid uses intelligent devices and digital communications to enhance the performance of the power system. The efficiency and reliability can be improved and active involvement by end users involved in the Smart Grid offer the opportunity to save consumers' money [87]. The main intelligent functions of Smart Grid are shown as Figure 27.

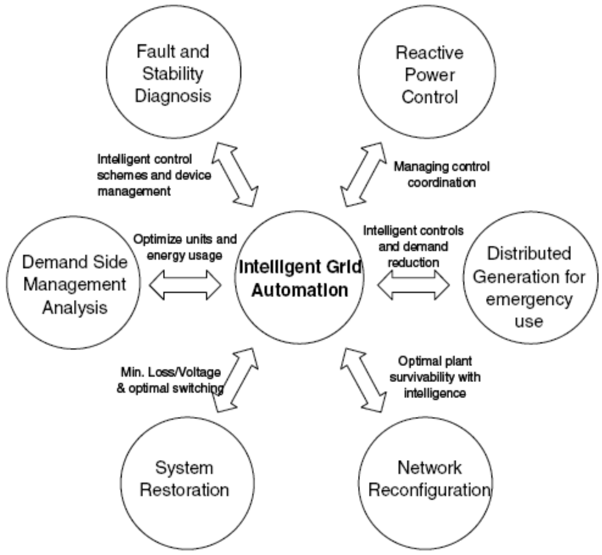


Figure 27. Functions of Smart Grid [87]

The basic concept of Smart Grid is to have system wide monitoring with data integration, advanced analysis to support system control, enhanced power security and meet the power demand as well as reduce energy consumption and costs. The ability of two-way communication between data sources and decision makers in the control centre with suitable latency is critical to the success of Smart Grid. Therefore communication infrastructures are required between customer's energy meters and the utility control centres via various communication media.

Most electric meters are still the traditional electro-mechanical meters that have been employed for many years. Recently, new types of electricity meter have been roll-out which are a digital energy meter with many functions that would be possible to provide more information at the customer's side and communications to control centres and are referred to an Smart Meter [88] in the UK. The Department for Energy and Climate Change (DECC) of UK government mandates that Smart

Meter should be installed in every household in the UK, about 47 million Smart Meters installed in 26 million properties by 2020 [89]. In the UK, Smart Meter refers to an electricity meter that records electric energy data in intervals by real-time sensors and power quality monitors, and then sends the information back to Meter Data Management Centre by two-way communication systems. The Smart Meter is used for monitoring and billing purposes to enable suppliers and customers to both have the real-time data as shown in Figure 28.

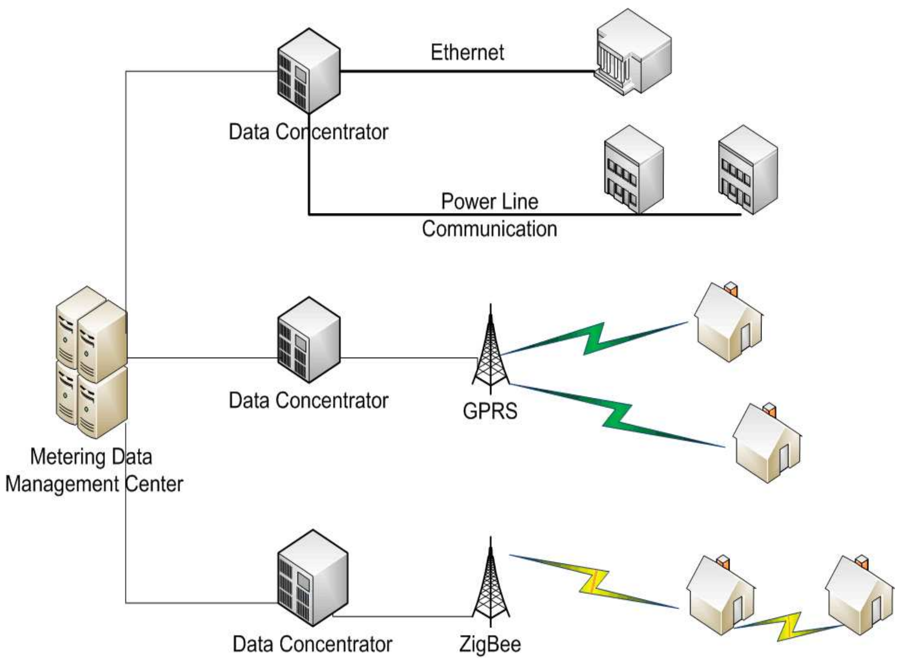


Figure 28. Smart meter communication model [90]

The energy saving and encouraging consumers to use renewable DG are achieved by Smart Grid and it is estimated that 2.6 million tons of CO_2 emissions can be reduced by 2020 [88]. This plan has been announced as the prerequisite of Smart Grid to implement the power flow management and renewable DG penetration. It is a direct way to show the benefit of Smart Grid to energy suppliers and customers by the real-time and accuracy data collection provided by the £8 billion scheme [88].

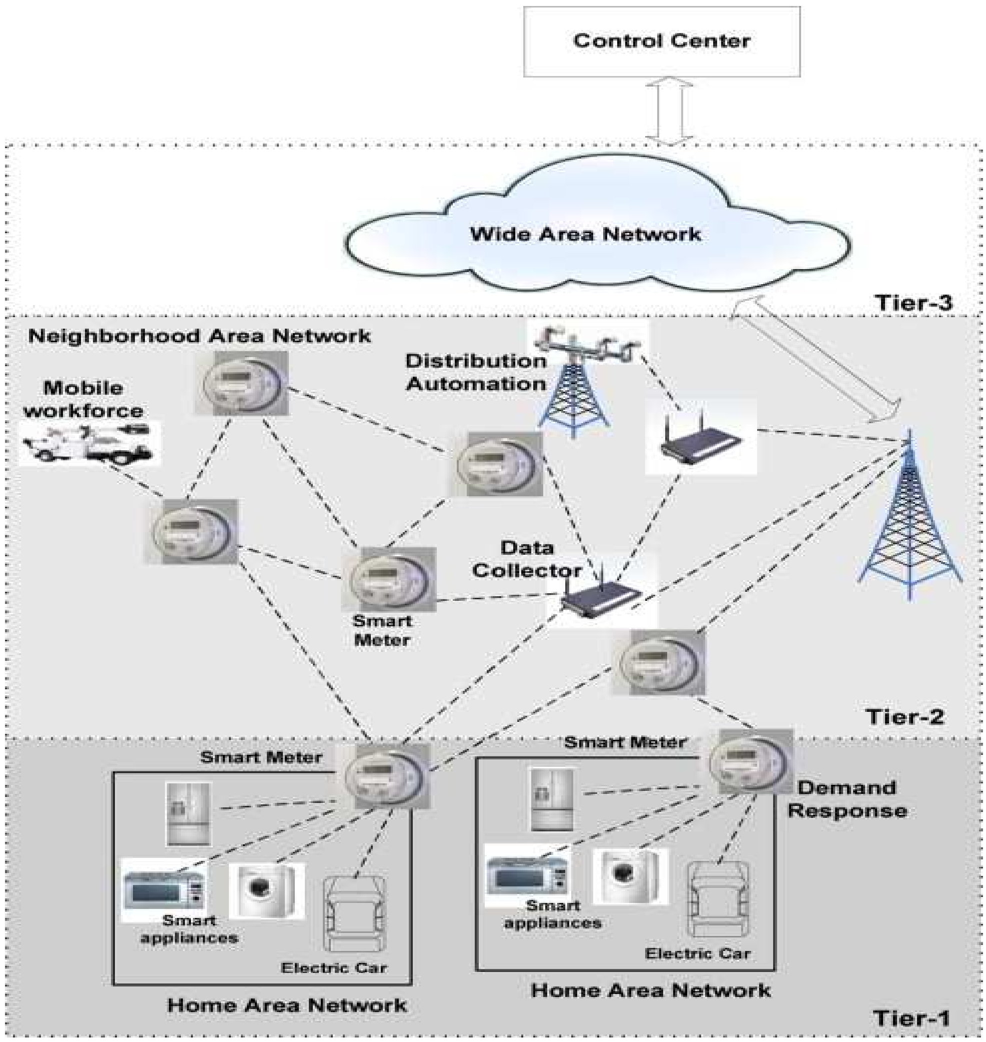


Figure 29. Smart Metering network [91]

Figure 29 illustrates the structure of Smart Metering system. As the backbone of Smart Grid technologies, Smart Metering is a subject that attracts a lot of attention all over the world due to its key functions and features. Smart Metering can provide customers with a choice of rate options such as time-of-use rates, prepay opportunities and smart application controlled demand reduction. Moreover, remote disconnect and reconnect; outage, blink and voltage monitoring; and remote real-time meter reading can be other effective operations for using of Smart Metering.

4.3 Voltage control with Smart Meters

In this thesis, the voltage control aspect of Active Distribution Networks (ADN) in Smart Grids with Smart Meters has been investigated. With the tendency to introduce the widespread use of power electronic and communication technologies in distribution networks, the operation of the network is more active and network condition can be critically assessed and appropriately control led to accommodate DG penetration.

Since the end users are expected to play a more dynamic role to participate in voltage control in order to have a reliable power delivery of high quality power in the Smart Grid, a data communication infrastructure is required to implement two-way communication between data measurement point and distribution network control centre. This is not considered to be adequately supported by the existing passive power systems where a single centralized control centre relying on Supervisory Control and Data Acquisition (SCADA) systems is used as the backbone of communication by DNOs [92]. To get the actual network status, Smart Meters which could have the feasibility to communicate real-time voltage measurements from customer's side to a network controller and therefore give benefits to a more flexible and coordinated voltage control. With this installed infrastructure, it will be for the first time possible to get real-time measurements of voltage and consumed power at customer's sites. This data can be used for improving and ensuring the voltage quality for customer and also be used to optimize the network operation of distribution system.

With the introduction of Smart Meters in a Smart Grid, the Quality of Service (QoS) can be improved in network which is more dynamic with bidirectional power flow defined as an Active Distribution Network (ADN) with increased capacity to adopt higher DG penetration [93]. The control and communication technologies are combined in ADN thus DNOs can manage the operation of network by introducing automatic control strategies under different network conditions to improve the power quality delivered to customers. With growing load and DG penetration, ADN could defer investment of network reinforcement or new network construction by introducing strategic replacement of aging asset [94].

In order to meet all of the above objectives, innovative technologies are required for DNOs to provide a dynamic control across an ADN. From the voltage control point of view, the objective of active network management is to control voltage profile of every node in distribution networks within statutory limits and maximizing DG output power. The potential function of Smart Meter as a real-time monitor installed in an ADN will lead to the voltage limits being used for the actual load and DG management instead of using the existing worst case assumptions. Although DNOs are not in charge of Smart Meter design and installation, the measurement of power flow, power factor, load demand and voltage profile can be achieved by developing the Smart Meter technology, which is being initially designed as power consumption meter for billing purpose only. The embedded sensor and communication system has the potential to integrate a powerful monitoring function. DNOs employ various communication technologies for SCADA via different communication media to collect and process the state information of distribution network then automatically control the devices by two-way communication function similar to that of the Smart Meter. Furthermore, the measurement data and communication infrastructure could be used more effectively by Distribution Management System (DMS) which is the core of ADN to improve the network operation therefore as a precondition for Smart Grid functionality.

Voltage control of a distribution network is one of the most important considerations to both power suppliers and consumers. The voltage magnitudes of busbars are required to be maintained within statutory limits for efficient, secure and reliable reasons. At the same time, proper voltage control can enhance system voltage stability and reduce power losses. In order to perform voltage control efficiently and smartly, a large number of different types of voltage control devices and power quality sensors will be required to be used at different locations in Smart Grid. These will include OLTC transformers, shunt capacitors, synchronous DG, Static Var Compensator, Converter-based Flexible AC Transmission Systems (FACTS) controllers such as Static Synchronous Compensator, Static Synchronous Series Compensator, Unified Power Flow Controller and Interline Power Flow Controller due to the dynamic reactive power and voltage control capability. Moreover, advanced voltage control schemes, strategies and software tools will be necessary to be utilised with voltage control devices to realize a properly coordinated operation [95].

Since the traditional distribution network designs are not considered Smart Grid technologies, voltage control devices and voltage sensors are only located at substations and sending-ends of transformers. However, the voltage control schemes are inaccurate due to complex power conditions and bidirectional power flows. More accuracy voltage information is required to support voltage control. Smart meters have the capability to realize real-time voltage measurement communication between consumers and network controllers by wired and wireless communication systems. The actual network status is observed, measured, submitted and analysed by Smart Metering technologies in DMS. The voltage control signals are issued to different related voltage control devices such as OLTC to correct for voltage problems like overvoltage and undervoltage across the whole networks. Therefore, a more flexible and coordinated voltage control is performed in a Smart Grid to provide an improved power quality to consumers.

Optimal Power Flow (OPF) is an economic control-based optimization method which can be used to optimize the Smart Grid network operation with real-time measured data. It compares different actions subjected to specific operating constraints and selects one of them to make an objective function to minimization [96]. With real-time voltage measurement, the voltage setting point for OLTC voltage control can be determined by an OPF application in DMS. The OLTC and coordinated voltage control schemes can be controlled following the optimization.

4.3.1 Distribution Management System

Distribution Management System (DMS) acts as an active decision support system with a collection of monitoring and control applications to issue control decisions to different devices in entire distribution network thus improve the reliability and QoS.

Conventionally, DMS makes decisions to disconnect or reconnect DG under several particular network conditions by strict operation policy since real-time network data is limited. However, with the development of Smart Grids, actual network status can be used as the input information for advanced DMS to optimize the coordination of operation options by classic OPF method. The objective function is the operation cost minimization in accordance with the technical statutory constraints of network [97].

For voltage control, several different types of voltage control devices are involved and controlled by coordinated voltage control system in DMS with the voltage measurement of network nodes, together with DG output power and energy storage. The management system makes control decisions to coordinate the controllers that operate OLTC with the other ancillary voltage control devices to provide improved voltage control performance. The amount of active DG curtailment and load shedding, charge and discharge of energy storage, reactive power control and OLTC operation are optimal regulated in DMS to achieve an active management of distribution networks [98]. This coordinated control of reference voltage setting point of OLTCs and reactive power regulation is based on the optimization algorithm developed from real-time network data and the schematic diagram of active management is illustrated as Figure 30 [97].

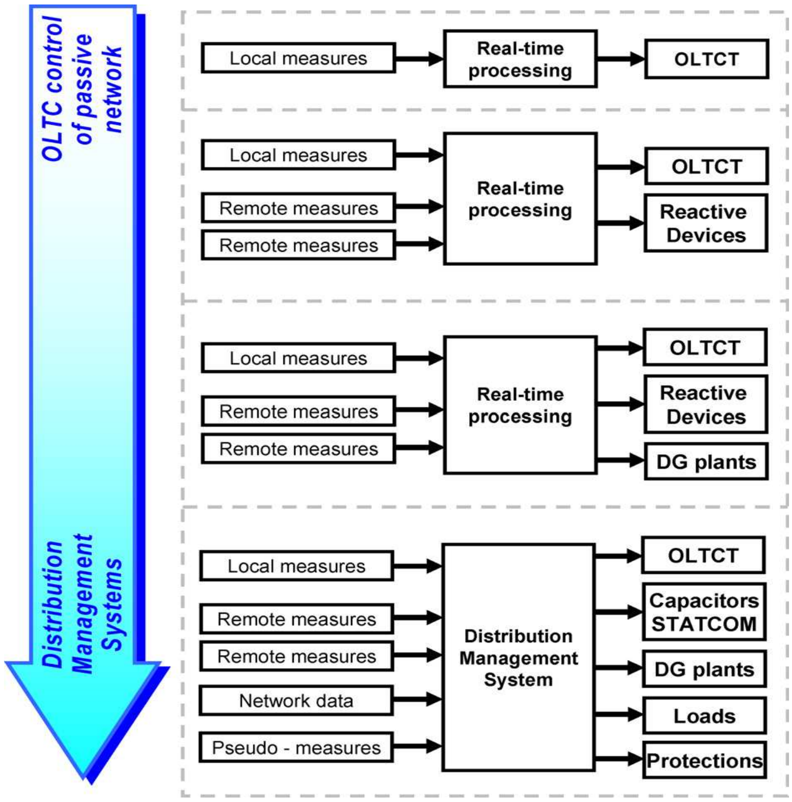


Figure 30. Active management of DMS [97]

In order to implement an improved solution for voltage control, intelligent techniques such as Artificial Neural Network (ANN), Fuzzy Logic Control, Tabu search optimization and multi-agent network are used to replace the conventional mathematical programming methods [99]. These intelligent techniques have the capability to solve the mixed-integer nonlinear programming problems and provide more flexible solution for cost functions and network constraints under varying network conditions by using more input network data to implement the optimization successfully [100].

4.3.2 Real-time voltage control

The location where power quality monitor will be installed have been recommended by IEEE standard [101]. These are generally at the substation, the end of feeder and near the busbar with sensitive loads for standard distribution networks. However, this recommendation encompasses conventional distribution networks where this kind of power quality monitor does not have the capability to monitor system attributes such as voltage and current at the busbars of the substation, OLTC transformers, customer meters and distribution switching devices [101]. The existing communication infrastructure is also inadequate on the existing distribution networks especially for HV and LV distribution networks. Therefore, remote voltage control by DNOs is limited due to that the limited number of monitored point which can measure attributes at customer sites with conventional networks. A large number of attribute monitors are required to be installed at transformers, load busbars along feeders and customer's point of connection in a Smart Grid. The observation level is not only performed at feeder level, but also customer's point of connection by extensive monitoring system of Smart Grid with communication with the objective to improve the power quality to consumers.

High speed data sensing will provide near real-time measurement for distribution network to enhance operation performance and security. The voltage monitoring function can be embedded in Smart Meter to acquire customer point level data within a few power-cycles. Improved ability to supply accurate information to the substation and consumer will be achieved by using Smart Metering, communication systems and DMS. A suitable system is shown in Figure 31 [102].

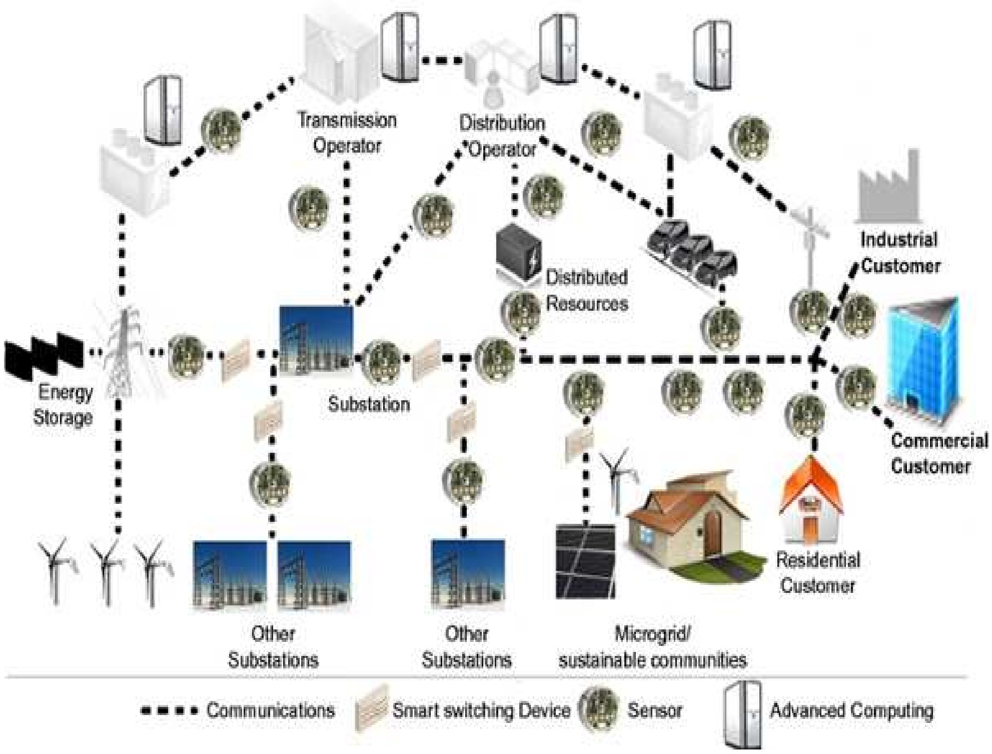


Figure 31. An illustration of real-time control in Smart Grid [102]

All Smart Meters act as sensors and must be able to communicate the real-time measurements to the nearest communication hub of the DNO control centre and deliver the control decisions to control devices within a short duration, typically less than 100ms for real-time voltage control [103]. Traditional multi-channel power quality monitoring system uses expensive and standard power quality monitors interconnected with complex web-based communication networks for a large network communication [104]. Compared with the web-based power quality monitoring system, the development of a Smart Metering scheme is employing Smart Meters as a means of monitoring and using two-way data communication. A central data processing system is one of the essential parts for data collection, calculation and power quality analysis. Real-time voltage control makes the transition possible from passive operation according to prediction and worst case scenarios to a dynamic management for distribution network. The active control can be implemented using network status simultaneously or very shortly before making control decisions to suitable control devices to achieved an optimal solution of combined operation of different equipments.

In order to achieve remote voltage investigating by real-time measurements, the communication technologies in Smart Grid must ensure all Smart Meters connected to network can be interactively accessed by two-way communication function of Smart Meter and DMS. The large amount of data from monitors, bandwidth and data rates of communication, noise level and bad data and varying network topology are the critical issues that Smart Grid must be considered for real-time voltage control [105].

4.3.3 Challenge

The near real-time voltage control must be supported by high speed of data sensing, low data latency for transmission, advanced power management systems and high speed computing to enhance system performance. A reliable and effective communication system is required to coordinate with the control devices.

With the growing number of DG using renewable resources which are integrated into distribution networks, more challenges are imposed upon DNOs in monitoring and controlling the system. Also due to the intermittent nature and technical barriers of DG technologies, there is further complexity of distribution network, resulting in the difficulties in measuring and communicating to control network. Most of monitoring and communicating technologies used in transmission network are unavailable in distribution networks [106].

Detailed and accurate data of the distribution network is essential for active management that the connectivity and impedance of distribution lines, in-line equipment, control devices, loads and DG forms the basis of real-time control. When some of the accurate and detailed data cannot be obtained, estimation algorithms can be employed as a foundation for operation. This is one of the primary challenges for real-time control. The complete field inventory can be updated by DNOs from the network design manual at the planning and design stage to provide an up-to-date network to provide accurate data from substation to load meter and DG locations [107]. Since this thesis focuses on the voltage control aspect, it is assumed that network data such as impedance of distribution lines and transformers, location of DG, network topology and the maximum or minimum load conditions can be acquired for the complete field inventory from DNOs.

The particular challenges to real-time voltage control for active radial distribution network in Smart Grid include communication interoperability, remote measurement, high performance computing for data processing and programming, throughput and latency of communication technologies and optimal management methods. Since there are a large number of voltage control devices operating in a distribution network and these will be maintained in service for many years, it is too expensive to replace all of the existing devices at one time and therefore coordinated capability must be addressed. Obtaining the necessary measurements is one of the greatest challenges for real-time voltage control. The existing distribution networks have a limited number of monitors and are generally geographically large in scale with massive feeders and laterals. The observable capability is therefore restricted and additional monitors with associated communication systems are required to be installed by DNOs in order to take the full advantage of real-time control. The percentage of sites requiring communications are predicted by ENA over 10-year and 20-year timeframe which are shown in Figure 32 [108]. The monitoring function can be embedded in Smart Meter system to collect voltage data of load, however most utilities do not have Smart Meter deployed with the additional monitoring function because this increases the cost of Smart Meter scheme [108].

Site Type	Quantity of Sites (% requiring comms) [Potential range of %]			Notes
	2011	2021	2031	
Control	10 *(100%)*	950 *(100%)* **	950 *(100%)* **	The increase is due to the distributed nature of Smart Grid Control, not Control Centre quantity.
132kV-33kV	6,450 (99%)	7,650 (100%) **	7,650 (100%) **	The small increase is largely driven by new large-scale generation plant (Wind Farms etc).
11kV/6.6kV	658,500 (7%)	694,500 (60%) *[30-70%]*	711,700 (89%) *[40-95%]*	This significant increase is driven by the need to control or monitor a far greater proportion of substations and automation points, plus any new medium-scale generation (Wind Turbines etc).
400V	238,000 (0%)	245,000 (17%) *[5-20%]*	245,000 (22%) *[10-30%]*	The increase is largely driven by the automation of LV Link boxes plus the need to monitor or control larger-scale EV Fast Charging Points.
Consumer	29.5m	31.8m *	34.1m *	The large quantities reflect the introduction of Smart Meters, however comms will be via the DCC not DNO.
Total	902,960 (6%)	948,100 (50%) *[25-60%]*	965,300 (72%) *[30-80%]*	

* Statistics from CLG, Household Projections 2008 to 2033
** Although these assets currently have comms, a higher service class may be required in the future

Figure 32. Predicted site quantities [108]

Overall, current DNOs still control the distribution networks by conventional methods to maintain the QoS. In order to move from passive to active network, the innovative techniques using information and communication devices to improve the control performance are required by DNOs. From voltage control point of view, the main challenges of transition to Smart Grid is the communication system with guaranteed throughput and latency to communicate data from measurement points to control centre via diverse communication channels of various bandwidth. Throughput is the average data rate that a successful message is delivered and latency represents the time delay of successful message delivery. To evaluate two-way communication performance for voltage control, latency usually presents the duration between measurements collected and control signal being issued to proper voltage control devices. Cost is another important factor that must be considered in order to establish cost-effective voltage control in Smart Grid.

In Section 4.4 and Section 4.5, the bandwidth and data rates of various existing communication technologies have been investigated to evaluate the throughput and latency performance for distribution network voltage control. The costs of different communication infrastructures are also presented to demonstrate the possibility of real-time voltage control using Smart Meters is practical in the short-term future.

4.4 Communication infrastructure

Smart Grid is generally characterized by bidirectional power flow in electrical network and information transfer in the communication infrastructure. The communication infrastructures can be divided into segments that include Home Area Networks (HAN), Local Area Networks (LAN) and Wide Area Networks (WAN) [109].

Wireless and wired communication technologies which have varying degrees of suitability can be employed in different sections of communication infrastructures to realise Smart Grid. The general wired technologies include Digital Subscriber Lines (DSL), optical fibre, Power Line Carrier (PLC) and wireless communication technologies using mobile telecommunication, Ultra High Frequency (UHF) radio, WiMax, ZigBee, Wi-Fi, microwave and Bluetooth [110]. Each DNO can select suitable mixed technologies to build their own communication networks that best match their regional needs.

The distribution networks include urban, suburban and rural areas thus the scale is geographically can be large and complex. In order to achieve a cost-effective communication with reliability and availability, each DNO must evaluate several criteria of the different communication technologies. This includes data rates, coverage, reliability, suitable voltage level and cost of the technologies.

4.4.1 Wireless technologies

In the past, wireless communication technologies have been limited in adoption for electricity networks due to the constrained bandwidth in the past. The data rates and interference issues of wireless technologies are comparatively low. However, the development of wireless data rates, the flexibility of configuration and the lower installation cost have resulted in the further consideration by DNOs for Smart Grid.

4.4.2 Wired technologies

Wired communication represents that data is transmitted over a wire-based communication technology. The bandwidth and the availability are higher than wireless communication however there are still many technical problems required to be solved.

Table 4 summarizes the main characteristics of each communication technology in terms of range, data rate, constrains and suitable voltage level. These technologies will depend on many relative factors in practical implementation nevertheless the technical information of each communication technology is adequate to be used for selecting the suitable technologies for voltage control purpose.

Table 4. Communication technology summary

Communication technology	Range	Data rate	Constrains	Voltage level recommendation
2G/GPRS/3G/LTE cellular	Long range, depend on mobile operator, GPRS national coverage	9.6Kbps/ 171.2Kbps/2 Mbps/ 100Mbps	Coverage in rural areas is limited, must rent from cellular carrier, high service cost	GPRS can be used in EHV and HV distribution networks for core communication, LTE can be used for last mile communication in rural area
UHF	40km point-to-point, 25km point-to-multipoint	9.6Kbps to 50Kbps	Low data rate	It can be used for some critical EHV and HV substation outside GPRS coverage
WiMAX IEEE 802.16	Up to 50km	Up to 70Mbps	Low data rate for long distance, spectrum availability depend on license holder	It can be used for last mile communication in rural area for connecting the customers point to control centre

Wi-Fi IEEE 802.11	100m	Up to 54Mbps	Limited coverage and cannot penetrate cement building obstacle	Wi-Fi can be used in LV network for monitoring in small buildings
ZigBee IEEE 802.15.4	10-100m	20-250Kbps	Low data rate, very limited coverage, cannot penetrate structures well	It can only be used in LV level for home automation
Microwave radio	40km	Up to 155Mbps	Must be installed on the building tops or masts, limited in urban areas since it cannot penetrate obstacle	It can be used in EHV distribution network for protection
Bluetooth IEEE 802.15.1	1-100m	Up to 24Mbps	Short distance, lack of security	It can be a candidate for local monitoring in LV level
DSL over pilot wire	8km	Up to 40Mbps	High deployment cost, pilot wire availability	It can be used in EHV substation for substation automation
Optical fibre	80km	Several Gbps	Extremely high installation cost and long installation time	It can be used in EHV distribution network and urban areas for high speed communication
PLC communication	15km	Up to 45Mbps	High noise and interference, signal attenuated for long distance	It can be used in LV level in urban areas for last mile communication

From Table 4, the communication technologies such as PLC, WiMAX and Wi-Fi can be used in LV distribution networks. ZigBee can be used for home automation due to its small size and low power consumption but it is not suitable for voltage control monitoring and communicating due to its low data rate. In urban areas, PLC can be used in LV level as the "last mile" communication technology to connect the data collected by Smart Meter from customer level to a contact point of LV network. The wireless technologies such as WiMAX can be used in rural areas for the "last mile" communication to connect Smart Meters to contact point of LV network. Optical fibre is recommended to connect two points for protection purpose due to its reliability, high throughput and low latency. However the high costs make it unsuitable for voltage control in distribution networks.

4.5 Latency and cost investigation

In order to achieve active voltage control by Smart Metering, throughput and latency are essential concerns for DNOs to guarantee that all of necessary voltage measurements are collected and transmitted to control centre and then the required control signal is transmitted to the control devices within acceptable response times. The Smart Metering implementation in the UK as proposed by the Office of Gas and Electricity Market (OFGEM) is that all the collected data is firstly transmitted to single centralized control centre like the present SCADA system through WAN [111]. However, the volume of data collected by Smart Meters will be extremely large in this centralized control since the number of Smart Meters in the UK will be about 47 million by 2020. The raw data size of basic flow is shown in Table 5. The message size per meter is estimated to be about 82bytes for one data collection activity from the Energy Network Association (ENA) Smart Metering Use Cases [112]. This data will be collected every half an hour and sent as cumulative data to DNO control centre every 3 months. The anticipated latency requirement of 12 hours has been specified by the ENA.

Table 5. Raw data size [113]

Data	Size (bytes)	Breakdown
Command /Request	25	The request can be used to schedule reads, to request reads on demand, to update meter, to control load etc.
Meter Periodic Data read	4	Real Power imported (kW)
	4	Reactive Power imported (kVAr)
	4	Real Power exported (kW)
	4	Reactive Power exported (kVAr)
	4	Micro-generation Real Power (kW)
	4	Micro-generation Reactive Power (kVAr)
	4	Voltage
	4	Power Factor
Confirmation/Notification message	25	Confirmation or failure notification

For real-time voltage control, the 12 hours latency requirement is too high to realize an effective control. The more demanding requirement of latency as defined by IEEE standard 1646 [114] is 1s and is more suitable for monitoring and control of external devices to substation as shown in Table 6 for power substation automation.

Table 6. Data delivery time requirement [114]

Message Type	Internal to Substation	External to Substation
Protection	¼ cycle	8-12ms
Monitoring and control	16ms	1s
Operations and maintenance	1s	10s

Since voltage can vary quite quickly and operation time of OLTC is general 10s-60s, the measurement of basic power flow needs to be delivered by Smart Meters with a time interval of 1 minute. In centralized control approach, the total message sizes is 3854Mbytes (82bytes*47million) for one interval data measurement, therefore the communication network with a capacity of 30Gbps is a prerequisite to meet the 1s latency requirement. If the latency requirement is extended to 10s, a 3Gbps data rate for the whole communication network is still required. At the moment this is impossible to be cost-effective. Also, it is not necessary to communicate all of the data to a single centralized control centre and therefore the communication network can be distributed. In the UK Smart Metering system, the active voltage control operation is defined to be implemented as part of substation automation in HV (11kV/6.6kV) distribution network according to the Smart Grid Use Cases [113]. The measurement data can be communicated and processed to the distributed control centre on HV network layer in order to implement active voltage control for one subsection of a power network as shown in Figure 33.

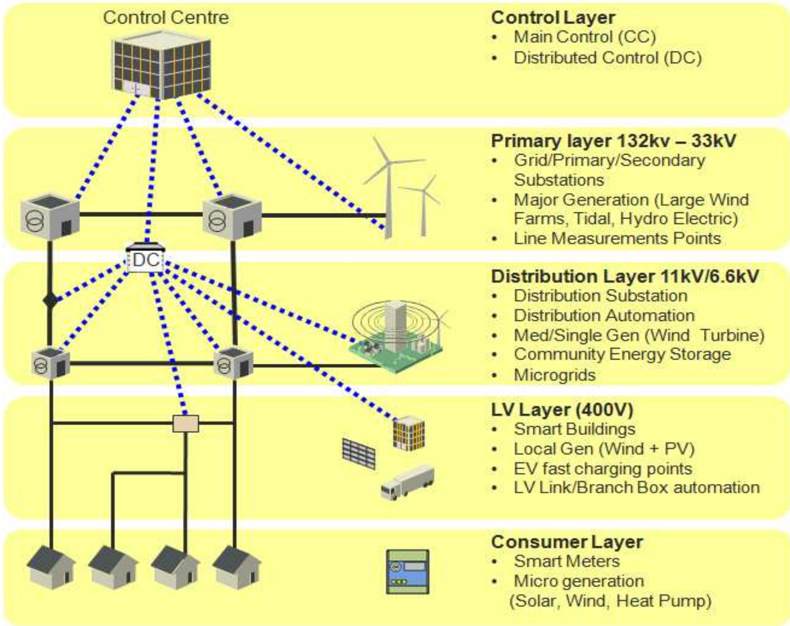


Figure 33. Smart Grid Layers [108]

Active voltage control requires the voltage measurement data of all monitor points to be delivered to distributed control centre and then proper control signal to be issued to control devices within strict guaranteed time to realize an ADN as DNO's Smart Grid. Thus latency of communication technology is one of the main criteria for building a suitable communication infrastructure. Since different communication technologies have their own technical and economical characteristics, the availability of technology to be deployed at each voltage level in distribution network is another factor that needs to be considered. More than one type of communication technology can be used to offer a subsection of the Smart Grid. Each subsection will have contact points to communicate data to relative contact points of other subsections.

Measurements of industrial loads, DGs and substations in HV distribution network can employ WiMAX, UHF and cellular technologies as WAN to communicate directly with the distributed control centre. Since the cellular technology does not belong to DNO this can be expensive service to rent and result in less cost-effective for large amount of use. The estimated cost of communication networks in the UK Smart Grid for some technologies by 2031 are shown in Table 7. Both capital and operational expenditure of fibre and microwave communication technologies per site are much more expensive than the cost of the other technologies. Therefore, PLC and Cellular are estimated to be used as the main communication technologies in a Smart Grid.

Table 7. Overall cost of communication technologies [108]

Overall cost by 2031	Capital Expenditure (CAPEX)	Operational Expenditure (OPEX)	Site Qty	Capex per site	Opex per site
Fibre	£14M	£1M	629	£22.018	£1,590
Microwave	£283M	£31M	7,971	£35,493	£3,889
UHF	£330M	£21M	80,956	£4,077	£259
Cellular	£1,354M	£99M	548,980	£2,466	£180
PLC	£140M	£9M	59,764	£2341	£150

Based on the study of Workstream 3 of the DTI/OFGEM Technical Steering Group, it takes the assumption that a generic urban network from 33/11kV HV substation down to LV customers includes six 11kV feeders and eight 400V LV substations on each feeder. It assumes that 384 households are supplied by one 400V substation [115]. An example of generic urban distribution network using different communication technologies is modelled when both the technical and economical characteristics are considered in Figure 34. PLC is used as the communication technology to transmit the data from Smart Meters of all households to the Contact Point (C/P) of LV layer and then the data is communicated to the distributed Control Centre (C/C) of HV layer via GPRS technology. The data of all HV Control Centre are transmitted to DNO's control centre using GPRS communication technology. The data size per measurement of one Smart Meter is estimated as 82bytes from Table 5.

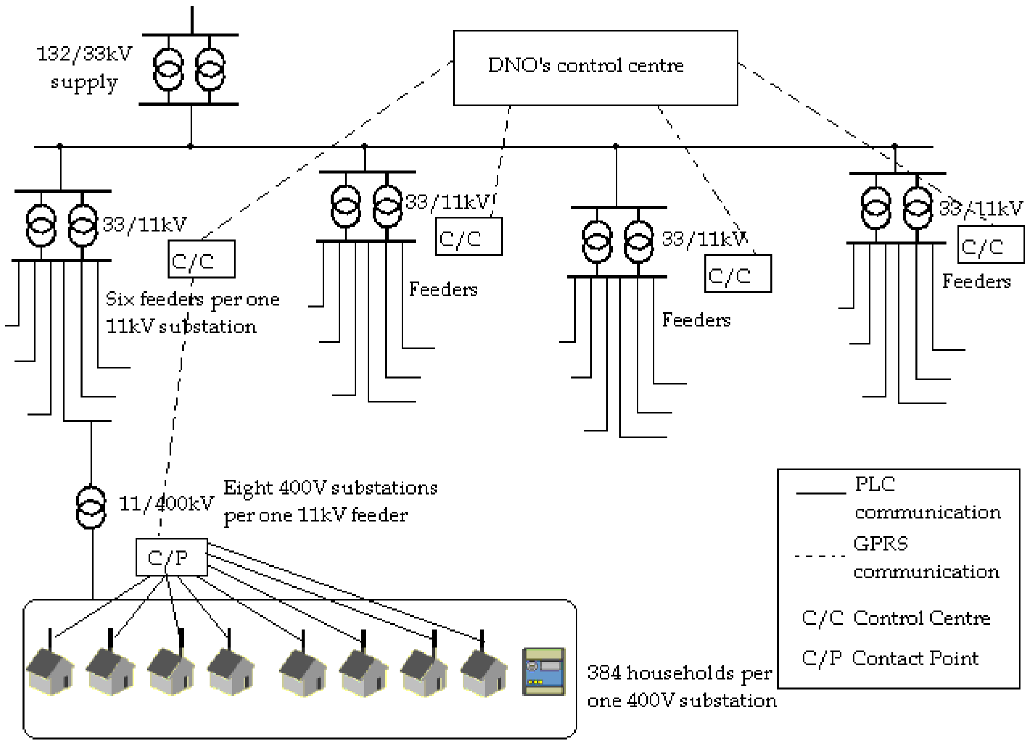


Figure 34. Generic urban distribution network example

The message size through one LV Contact point per measurement is estimated as 31.5Kbytes (82bytes data per Smart Meter measurement * 384 Smart Meters in all households per LV substation). The message size of one HV substation per measurement is assumed as 1.5Mbytes (82bytes data per Smart Meter measurement * 384 Smart Meters in all households per LV substation * 8 LV substations per HV feeder * 6 feeders per HV substation). The total message size per measurement from HV substation to DNO's control centre depends on the number of HV substations in one DNO's control region. The expected latency of PLC technology which has 30Mbps rate from Smart Meters to 400V LV Contact Point is estimated as 0.01s (31.5Kbytes/30Mbps). When only one HV substation is considered, the expected latency of the example network is estimated as 70.09s (1.5Mbytes/171.2Kbps) from LV Contact Point to HV Control Centre. The latency of different control subsection size is listed in Table 8 for the example communication solution. There will be other networks using different communication technologies and the example network solution considered is for generic demonstration.

Table 8. Latency of example network

Region size / Latency	One HV substation	Five HV substations	Ten HV substation
PLC (30Mbps)	0.01s	0.01s	0.01s
GPRS (171.2Kbps)	70.09s	350.47s	700.93s
Total	70.10s	350.48s	700.94s

From Table 8, it can be seen that the wired PLC technology can communicate between Smart Meters and Contact Point (C/P) of 400V LV layer with a low latency about 0.01s. However the GPRS which has typical 171.2Kbps rate is required to transmit the data from LV Contact Points (C/P) to HV Control Centres (C/C) and there is an extremely high latency due to the large data size and low communication rate. This makes it impossible to meet the latency requirement for real-time voltage control. Furthermore, in a practical system a GPRS transmitter might cover hundreds of HV substations therefore the communication network would offer a worst level of data communication performance with a higher latency.

The latency of the example solution and cost of each communication technology demonstrate that the existing communication infrastructure is inadequate to achieve a real-time voltage control using the Smart Meters technology as being implemented in the UK due to both the structure and system capability.

4.6 Summary

Due to the focus on energy conservation and emission reduction, green energy, sustainable development and environmental issues, Smart Grid technology has become the proposed solution to provide self-healing, high power reliability and quality, operation with multi-directional power flow and more energy service choices for customers. Smart Grid uses more consumer-interactive facilities in order to make the grid truly intelligent. There are many challenges and problems need to be addressed with the use of the Smart Grid. The high penetration of DG in a Smart Grid has a significant impact the voltage control and makes it more difficult to control steady-state voltages. Smart Meters have the potential to be used as the sensor to monitor the voltage measurement and communicate the collected data using two-way communications.

This chapter has overviewed basic concept of Smart Grid and its intelligent functions together with the introduction of Smart Meter. How Smart Grids will influence voltage control in distribution network has also been discussed. The Smart Meter is considered to provide the necessary voltage information from all sensors to the control centre in order to establish a near real-time control. The Smart Metering system as being installed in the UK generally considers the control structure is centralized which can provide the global optimal performance. However, the volume of data is too large to be processed within the required time for effective control. Thus a decentralized control structure is recommended for voltage control in distribution networks. The latency and cost of existing communication technologies has been discussed and it has been demonstrated that active voltage control with Smart Meter is inadequately supported by the existing communication technologies to meet the real-time requirement. Moreover, the large scale deployment of Smart Meter in the UK has limited capability to offer voltage control function which further constrains the possibility of real-time voltage control in distribution networks.

Chapter 5

Distributed generation impact on OLTC voltage control

This chapter explores the DG impacts on voltage control centred on the using of OLTC transformer with AVC relay in 11kV distribution networks. The conventional operation of OLTC with AVC relay and general control strategy to control voltage in distribution networks without the consideration of DG penetration by DNOs are introduced first. The voltage level to which most DG connected is presented briefly from a commercial vantage point and then the current standard regulation and operation policy for DG integration is mentioned. How the DG impacts on the OLTC voltage control is discussed and a series of model by Simulink of MATLAB® has been simulated to demonstrate the impacts of different DG technologies. The DG connected networks with different X/R ratios of distribution lines using overhead lines or underground cables has also been simulated to demonstrate that the inefficiency of reactive power voltage control in lower voltage distribution networks. Some enhanced OLTC voltage control methods are discussed with their advantages and disadvantages.

5.1 Introduction

The DNOs employ OLTC equipped at primary substation transformer to control the secondary voltage within the limits imposed by ESQC in HV distribution networks in the UK. The design and expense of networks are determined by this voltage requirement. The OLTC is generally controlled by AVC relay to maintain the transformer secondary voltage at a constant value within a deadband therefore offsetting the voltage change due to primary voltage disturbances and voltage drop caused by load variation with time of day and season.

To avoid unnecessary tap changing operation due to short time voltage fluctuations, a time delay is used in the AVC relay when measured voltage is over deadband. The OLTC is operated when the measured voltage is still out of range after the time delay. In order to control voltage of remote point in feeders, LDC is provided with the AVC relay to change the reference voltage setting point of the relay dynamically based on measurement of secondary current of the power transformer and the sending-end busbar voltage. The compensation parameters of line impedance are provided by off-line power flow studies that the voltage profile is predictable under maximum and minimum load condition. Therefore the OLTC reference voltage setting point, which is deadband centre, is generally chosen according to the maximum voltage drop between transformer sending-end busbar to the most affected feeder end caused by winter peak load by DNOs in practical operation to ensure that the minimum load voltage does not fall below the lower limit. This method causes the voltage along feeders to be higher than necessary for most of the time. The load voltage is just below the maximum allowed under the minimum load condition. The conventional method is based on passive concept of distribution networks that the maximum voltage is at transformer sending-end busbar and decreases along feeders without any connected DG.

In order to meet the current and future ambitious target to reduce carbon emission by governments and solve the distribution constraints caused by difficulties in site selection of large power stations, numbers of DG are integrated into distribution networks to provide local power supply such as solar PV, fuel cells, wind turbines and cogeneration etc. The DG capacity is growing and the characteristics of different DG technologies can cause operation problems on voltage control in distribution networks which are original designed for networks without any generation and the power flows from substation to feeder ends. The power flow in the feeder is changed and hence voltage control is influenced as well when DG is connected to feeders. The DG impacts on conventional OLTC voltage control is assessed in the following schemes under network constructions using different distribution lines and some enhanced OLTC voltage control schemes are discussed.

5.2 DG impact on voltage control

When DG is connected to a feeder of a HV substation in distribution network, the active output power of DG reduces power flow from primary substation thus the equivalent load measured by AVC relay is less than actual value since transformer secondary current is reduced and hence the voltage drop along the feeder is also reduced. Therefore, a tap changing operation occurs by AVC relay to lower sending-end busbar voltage in order to compensate the reduced voltage drop caused by DG connection. However, the voltage of feeders without DG connection may be undervoltage if DG is connected to the most affected feeder during the maximum load condition.

When the active output power exported from DG exceeds the load demand of feeder, the power flow is reversed and the voltage of DG connection point is higher than transformer secondary voltage. When the DG connected point voltage is above the upper voltage limit, the power of DG is curtailed by 50% or 100% in some practice [116]. The DG capacity that can be connected is limited to the level at which voltage limit is not exceeded under maximum generation and minimum load condition. Since there are very few monitors in feeder of HV and LV distribution network, the AVC relay can only measure the voltage and current at substation, the direction of power flow is not considered in a conventional control strategy with unidirectional power flow assumption and reversed power flow may result in LDC operation to make voltage situation even worse [27]. Moreover, the voltage can no longer be predicted with presence of DG that normally is non-dispatched. The voltage is significantly influenced by many uncertain factors such as DG location, intermittent nature of renewable resources, DG size, load conditions and network constructions [117, 118].

The cost-effective accommodation of DG penetration to distribution networks is a main challenge for DNOs. The penetration level of DG has grown and distribution networks that were designed and controlled with the assumption of unidirectional power flow are changing to a bidirectional power flow networks. The unaccepted voltage rise of the DG connection point caused by large DG active power output is the main problem for the limitation of DG capacity while reversed power flow is a key affected factor for OLTC voltage control in 33/11kV distribution networks [119]. This is explored in further detail in the following section.

5.2.1 Voltage rise of DG connection point

The voltage of DG connection point may rise depend on output power of DG, load conditions and power factor when DG is connected to a feeder of distribution network. The simplified one-line 11kV distribution network with DG connection at feeder end is shown as Figure 35 to illustrate the DG impact on voltage. The V_S is sending-end busbar voltage of 33/11kV OLTC transformer, Z (R+jX) is the line impedance and V_L is the voltage of load busbar. For conventional distribution feeders which are radial and without any DG, the direction of power flow is from the substation towards the loads. Therefore the highest voltage of one distribution feeder occurs at the sending-end busbar of OLTC transformer and decreases along the feeder to the end.

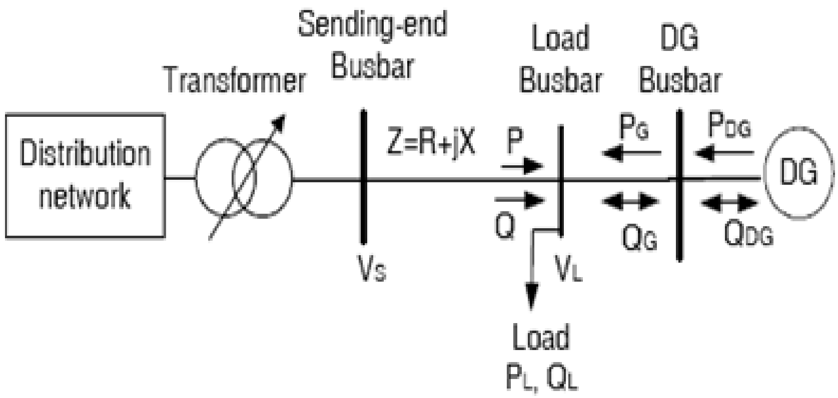


Figure 35. An 11kV distribution network with DG connection

The typical voltage drop equation is given below:

$$V_S - V_L \approx \frac{RP + XQ}{V} = \Delta V \tag{10}$$

When DG is connected to the end of feeder, the voltage profile along feeder is changed that the output power of DG (P_G is active power output and Q_G is reactive power output) needs to be considered as well. The voltage drop from sending-end busbar to load busbar can be written as:

$$\Delta V = V_S - V_L = (R + jX)\frac{P - jQ}{V_L} \tag{11}$$

where P = P_L−P_G and Q = Q_L±Q_G (+Q_G when the DG absorbs reactive power and -Q_G when the DG exports reactive power). Since the imaginary part is much less than the real part of equation (11), the $j\frac{XP - RQ}{V_L}$ is generally small and can be ignored, especially in distribution networks using the overhead line [3]. Then the approximately voltage drop equation (11) can be simplified as equation (11):

$$\Delta V = V_S - V_L \approx \frac{RP + XQ}{V_L} = \frac{R(P_L - P_G) + X(Q_L \pm Q_G)}{V_L} \tag{12}$$

When the worst case condition is considered, P_L and Q_L are zero as minimum load. The reactive power of DG exported or imported has less impact on voltage than the active power and the DG reactive power is not considered to be involved for voltage control in the UK [120] which is explained in detail in Section 5.2.3. Therefore the reactive power Q_G is considered to keep zero by DG exciter system or external reactive compensation devices like shunt capacitors to provide power at unity power factor. The voltage difference between the sending-end busbar and load busbar is as equation (13):

$$\Delta V = V_S - V_L \approx \frac{RP_G}{V_L} \tag{13}$$

The active output power of the DG results in voltage rise from sending-end busbar to load busbar as equation (13) in minimum load condition. When DG active power exceeds load demand in other load conditions, the V_L is higher than V_S. The voltage may drop below lower voltage limit when DG is out of service during peak load time if the sending-end busbar voltage is maintained at a low voltage level. The worst voltage rise situation occurs at the maximum generation with minimum load condition.

The conventional reference voltage setting point of AVC relay is chosen under the winter peak load condition without DG connection thus the voltage of sending-end busbar are normally just below the upper voltage limit. The voltage rise caused by DG integration can easily be over the set limits and therefore at an unaccepted level. The active power curtailment of DG can reduce the voltage rise problem caused by DG connection but this method is not recommended since it constrains the capacity of DG penetration at HV and LV distribution networks.

Lower the voltage of sending-end busbar when the voltage of DG connection point is over upper voltage limit due to large DG active output power will effectively overcome the limitations on DG capacity thus more power is allowed to generate to networks. However, this method requires the reference voltage setting point of AVC relay must be controlled dynamically according to DG output power and state of connected networks. The full knowledge of network state cannot be obtained with current monitoring level even in the short term or medium term future. Therefore DNOs need more reliable and effective OLTC voltage control algorithm to mitigate the voltage control problems with high penetration of a wide variety of DG.

5.2.2 Reverse power flow

In a traditional power system, the electrical power is transmitted from transmission networks to distribution networks and then distributed to consumers via distribution feeders. Both active and reactive power flows from substation to feeder end in conventional networks without DG penetration. The design and operation of distribution network has been established for a long time with unidirectional power flow. However, DG connected to distribution feeders may cause the assumption of unidirectional power flow to be invalid when DG penetration is high and DG output power exceeds the local load demand. The power flow can be reversed from DG connection point to substation.

The conventional OLTC voltage control strategies do not have ability to solve the problems caused by high DG penetration since they designed strongly depended on the assumption of unidirectional power flow. The LDC method generally used in OLTC voltage control with AVC relay is based on the unidirectional power flow thus it only measures the magnitude of secondary current of OLTC transformer to compensate the voltage drop from sending-end busbar to the feeder end by simulated distribution line impedance in order to maintain the voltage at remote point within limits [15, 21].

When DG is connected to the feeders, the power flow is changed and the secondary current of OLTC transformer measured by LDC is no longer proportional to the load current. The DG impact on LDC is not significant when the DG power is not large. But with high DG penetration which exceeds local load, can result in LDC inadequate by reversed power flow [21]. If the DG output power is equal to local load in the most affected feeder, the secondary current of OLTC transformer is nearly zero, hence LDC reduces the reference voltage setting point of AVC relay to 1.0 pu. An undervoltage may occur at the other feeders which are supplied by the same substation. The undervoltage situation is significant under maximum generation and maximum load condition. The magnitude of reversed current causes voltage rise from the substation to the DG connection point but LDC uses this voltage rise as a voltage drop. The sending-end busbar voltage is therefore increased by OLTC with LDC method and the voltage situation along feeder is much worse due to the bidirectional power flow in distribution networks. This error is the operation of LDC with the reversed power flow impacts on voltage rise significantly under maximum generation and minimum load condition.

5.2.3 DG impacts under different X/R ratio

With present of DG, the amount of reactive power which can be injected or consumed depends on the generator and type of network [14]. When DG generates reactive power, the voltage rise of DG connection point is increased according to the equation (12). If the DG absorbs reactive power, the impact will depend on the DG active and reactive power relative to the active and reactive load demand and the X/R ratio of network line [121]. Therefore, the voltage of DG connection point can be reduced by reversing the reactive power flow to mitigate the voltage rise problem. The asynchronous generator, exciter system of synchronous generator or some reactive power compensation devices can be used to absorb reactive power and operate at leading power factor. However, the efficiency of reactive power used for voltage control is highly depended on the X/R ratio of distribution lines.

Generally, distribution networks are classified into urban, suburban and rural areas according to load densities. In the UK, long overhead lines are normally used in rural area in distribution networks. One practical distribution network is taken here as a typical example, the 60% of HV and LV distribution network assets are underground cables which are used in urban and suburban area [122, 123]. The load proportion of three classified areas is shown in Table 9, indicates that load in rural area only take a small percentage and the most load is in urban and suburban areas using underground cables as the power distribution lines.

Table 9. Load proportion [124]

Area classification	Load proportion
Urban	52%
Suburban	41%
Rural	7%

The typical parameters of underground cables and overhead lines used in UK distribution networks are obtained from the Network Design Manual published by one of DNOs [125]. The X/R ratio of underground cables is generally from 0.1 to 0.5 and the X/R ratio of overhead lines is generally from 0.6 to 1 in HV distribution networks. The X/R ratio is even lower in LV distribution networks [122].

In cable networks, the need of reactive compensation devices can be reduced by the consumption of reactive power by DG. A drawback of reactive power voltage control with DG is the increasing current in the lines thus an increase of power losses and the voltage changes caused by injection or consumption of reactive power will decrease significantly with distance [126]. Since the X/R ratio in distribution networks is typically much lower than in transmission networks, the reactive power voltage control with DG is not efficient for HV and LV distribution networks mainly using underground cables. When DG is connected to overhead lines, which have higher X/R ratio in weak rural area, the more effective performance of voltage control by reactive power with DG is provided. However, at this situation heavy demand is placed on DG to absorb reactive power. This may result in additional operational costs for

DG and increasing in power losses [127]. Therefore, active power and resistance of distribution lines are the dominant impact factors for voltage in HV and LV distribution networks.

In order to reduce the voltage rise caused by DG connected to rural distribution networks by overhead lines, upgrading the conductor of overhead line to larger conductor size is effective. The resistance of 300mm² HDA Butterfly conductor is 0.0892Ω/km and is much smaller than 0.550Ω/km of 50mm² AAAC Hazel conductor. The reactance of these two type conductors are similar that is 0.316Ω/km and 0.351Ω/km respectively [125]. The X/R ratio of large conductor is about six times higher thus the voltage profile along feeder is smoother due to the smaller resistance. The higher X/R ratio also improves voltage control performance by reactive power. Therefore, the upgrade of conductor in 11kV overhead lines can be effective to reduce the line impedance and provide an improved voltage profile. However, the cost of fully rebuilding the overhead lines in HV distribution networks is very expensive about £33.5k/km [128] and this whole network reinforcement method is not recommended due to it is passive and uneconomical.

Reactive power management has not yet been encouraged by appropriate pricing mechanisms as a means of voltage control in the UK [127]. A common reactive power charging policy is implemented in force by all electricity supply companies to charge the consumers who import or export reactive power from 2012 in the UK [129]. When the imported or exported reactive power measured in kVArh does not exceeds 33% of the total active power measured in kWh used by consumer in any half-hour period, the reactive power charge is free. When reactive power exceeds the 33% threshold is seen as a reactive excess which is chargeable at the rate appropriate to particular tariff by different DNOs. Since the DG active power consumption is much smaller than the active power output meanwhile the reactive power absorbed by DG in order to reduce the voltage violation is seen as a reactive excess hence a high reactive charge has to be paid by DG owner. The excess reactive charge policy for conventional distribution networks does not support the voltage control using DG reactive power management therefore the DG output power factor is generally controlled between 0.95 to 1 to avoid extra reactive power charge by DNOs [127].

As discussed before, voltage control in HV and LV distribution networks using reactive power of DG is not effective due to the much lower X/R ratio of distribution networks compared to that of transmission networks. The impact on voltage is not significant by the VAR management of DG but the loss is increased. Moreover, the current pricing mechanism for reactive charge further limits the voltage control ability of reactive power by DG in typical distribution networks. The most effective voltage control method is still OLTC voltage control due to the structure and property of HV distribution networks [126]. A more reliable and effective algorithm of OLTC voltage control is required by DNOs to accommodate the high level of DG penetration.

5.2.4 Different DG technologies impacts on voltage control

The reliability and certainty of operation in distribution networks is affected by DG penetration because most DG technologies use renewable energy resources and the DG output power is non-dispatched. The reference voltage setting point of OLTC voltage control is chosen depended on load pattern and power flow calculation in order to estimate the voltage drop from substation sending-end busbar to the feeder end in conventional radial distribution networks with unidirectional power flow.

The intermittent and stochastic nature of most renewable energy resources such as wind, solar power or water flow which results in the DG output power cannot be dispatched according to the variation of load demand at different time of the day in different seasons. The renewable resources varies a lot for different seasons as well therefore the bidirectional power flow occurs in distribution networks without accurate prediction [130]. Moreover, the monitoring level of distribution networks is much lower than transmission networks therefore the steady-state voltage of distribution networks is uncertain using conventional OLTC voltage control strategy with DG penetration.

The location of some larger renewable DG has to be far from loads and substations due to the geographical characteristics of energy resources such as wind farms or small hydro plants which are connected to radial feeder ends by long overhead lines [131, 132]. Since the X/R ratio of weak rural distribution networks is low and resistance is high, the long distance from the DG connection point to substation results in significant voltage rise during maximum generation and minimum load condition.

The voltage variation in distribution networks becomes more complex with higher DG penetration of different DG technology characteristics. For example, ICE and cogeneration which generally use synchronous generator can export active power meanwhile absorb or export reactive power according to the DG exciter control system. Generally, the power factor of these types of DG using synchronous generator is controlled constant as unity power factor in order to supply more active power and avoid the reactive charge from DNOs for penalty. Therefore OLTC voltage control is impacted significantly when the magnitude of DG active power is larger than the relative loads. If the synchronous generator is controlled at voltage control mode, the reactive power is exported or absorbed when the voltage setting is achieved [133]. The reactive power of DG has less impact on OLTC voltage control but limits DG penetration into distribution networks.

The asynchronous generator is used in small and medium sized wind turbines to generate active power. However the operation of induction generator requires reactive power from grid. The capacitor bank is used to compensate the reactive power demand of wind turbine. The stochastic and intermittent nature of wind power has a much more serious impact on voltage violation in distribution network in short term [134]. The export power of wind farms is fluctuated depending on wind speed thus the highest generation from wind farms is normally at night where there is light load demand of distribution networks. The reversed power flow and voltage rise are the restriction of wind generation. In the daytime, the low level of generation from the wind farms is not helpful for peak load reduction. And what's even worse, the fluctuating bidirectional power flow through OLTC transformers is kept at a high level during all the day and results in the lower life cycle of OLTC transformers.

The solar PV system is connected to grid through power electronic circuit that DC/AC inverter and control system are used to generate power at power factor between 0.95 leading to unity. The potential PV impact on the grid is voltage rise for large PV plants up to MW scale. The PV panel installed for domestic use is normally small scale and is helpful to reduce demand during the day time. The harmonic current caused by PV is integrated into networks hence may cause voltage fluctuation [122].

The major concern of DG penetration focuses on the voltage control in distribution networks that the high penetration level significantly impacts conventional OLTC control and feeder characteristics [67, 127, 135]. Without restriction, the presence of DG may cause the voltage rise above statutory limits and the voltage variation may result in more frequent operation of the OLTC. The operation policy for DG integration using by DNOs are introduced as follows to demonstrate active control of distribution networks is not a common practice.

5.3 Standards, regulations and operation policy

The presence of DG is connected to distribution networks as a solution to maintain the short-term economic efficiency of power industry at the same time meet the carbon emission target from government. The small scale DG technologies with less carbon emission are environmentally friendly and close to load thus reducing system losses. Renewable power generation will benefit significantly through a mechanism of Renewable Obligation (RO) [136] that rewards due to the power from renewable resources are green and clean. The 15% energy demand in the UK from renewable resources is legally government committed to be achieved by 2020. The introduction of renewable resources will result in a high level of DG penetration of distribution networks in the UK [137].

The voltage deviation and bidirectional power flows caused by high level of DG penetration have significant technical and commercial impacts for distribution networks. At present, many countries have established some standards and regulations to cope with immediate technical issues of DG interconnection and operation in distribution networks in practical implementation. However, there is not a defined generalized standard to interconnect DG to distribution networks to date. The interconnection regulation in Europe is based on country-basis and in the USA is state-basis [138, 139] however there are some regions without specific regulations and in the UK the DG interconnection regulation is classed as an engineering recommendation. The DNOs have the responsibility to provide interconnection of DG into local distribution networks [140].

The IEEE 1547 is a standard developed as a guide to implement DG connection that is regulated to prevent problems to distribution networks in the USA [141]. This IEEE 1547 for DG interconnection with power systems indicates that the installed DG may neither cause any voltage violation over the statutory limits of power system nor regulate the local voltage actively [142]. The unity power factor is recommended in this standard for DG operation and the actual limits of 0.9 from leading to lagging are provided by a power factor compensation for local load. This standard constrains the DG penetration capacity in many existing distribution networks hence the DG economical installations to produce a large amount of power on-site cannot be achieved.

To date in the UK, DNOs have the responsibility to design, operate and maintain the distribution networks to distribute high quality power to all customers who are mainly load consumers. Conventionally, the voltage levels of distribution networks are considered under extreme load conditions (minimum and maximum load demand) to ensure the voltage is within the statutory limits. This method is effective due to the predicted voltage state by load demand of distribution networks. When DG is connected to networks, the objective of DG is to deliver the maximum power to networks in order to obtain the maximum payment. However, the operation of DG is infeasible to be controlled by DNOs and the presence of DG make the state of network unpredictable, nevertheless a similar practice based on worst case scenarios has been adopted by DNOs to make decisions to control the voltage of distribution networks for any possible DG and network conditions. Typically, these worst case scenarios are no generation and maximum load, maximum generation and maximum load, maximum generation and minimum load. The DNOs determine the capacity of DG that can be connected to networks under these worst case scenarios to ensure the voltage is maintained within limits irrespective of whether DG is connected or not.

This passive common policy operates the voltage control in distribution networks to avoid the voltage problems caused by high DG penetration however constrains the DG capacity significantly. At present, DNOs can only connect a restricted amount of DG capacity into distribution networks to prevent any possible problems caused by DG. There is little anticipation to implement major network reinforcement to solve the problems in the short-term condition because of the massive investment cost [106].

Since the voltage rise is the main factor to limit DG connection, especially in rural distribution networks, DNOs suggest that some DG is preferred to be connected to higher voltage networks to reduce the overall voltage impacts. However, from the commercial point of view the cost of DG installation is sensitive to connection cost which is increased significantly when connected to distribution networks of higher voltage level. The more expensive cost of high voltage connection results in DG to be connected to distribution networks of lower voltage level which is preferred by the owner of DG [14, 143].

In practice, the DG connection policy from individual local DNO determines the capacity of DG that can be connected to which voltage level. These policies largely depend on DG size and the topology of local distribution networks. Different networks have various parameters and different load curves thus a well-defined policy of DG connection to distribution networks is not possible to be established for universal use across the UK.

The individual-case basis of DG connection is used by DNOs in the UK complied with relative power quality standards defined in engineering recommendations [140, 144]. Typically, the DG size up to 500kW could be connected to 415V distribution networks, 5MW DG to 11kV distribution networks and up to 20MW to 33kV distribution networks in the UK [14]. In France, the DG size between 10MW to 40MW may only be connected to networks above 50kV, and DG size more than 40MW is not allowed to be connected below 225kV [11]. The general rules for selecting the voltage level of DG connection point in Germany are shown in Table 10.

Table 10. General rules for DG connection level in Germany [145]

Rated power of DG	Voltage level of network
≤30kW	LV networks without verification
30 - 200kW	LV or HV
0.15 - 20MW	HV
15 - 80MW	EHV

These general rules are used to determine the voltage level for DG connection in distribution networks as a guideline for DG installations. They are not only for the commercial success of individual DG project but also for the general level of DG penetration in distribution networks.

The distribution network is totally changed due to the DG connection from both technical and commercial points of view. The general regulations and standards adopted by DNOs are based on the rule that DG integration does not impact on the power quality supplied to consumers and plays a role of negative load in networks. Since distribution networks are expected to be developed into open-accessed based frameworks, DG can play a new role as power supplier not just a negative load. Hence DNOs are required to enable DG to participate in distribution network operation to develop an adequate regulatory and commercial framework. Although a number of operation technical issues are solved in the Report of the OFGEM/DTI Embedded Generation Working Group [146], there are neither technical nor commercial mechanisms to allow DNOs to optimally connect DG to distribution networks at the present.

5.4 Simulation of OLTC voltage control considering DG penetration

5.4.1 Introduction

The voltage limits of 33/11kV distribution networks defined in the ESQC is ±6% of nominal value. The DNOs usually apply ±3% on voltage variation as the limits at network planning stage in order to ensure the voltage of every node in 400/230V networks is within the statutory limits +10/-6% of nominal value. However, the ±3% limit for network planning has been ignored and the ±6% is used in the following generic simulations in order to demonstrate the impact of DG penetration more obviously. Since the substation of 11kV distribution network is the lowest voltage level equipped with OLTC transformer to control the voltage of sending-end busbar and most DG is connected to 11kV voltage level due to economic considerations, the distribution networks used in this thesis are 11kV distribution networks which are supplied by 33kV distribution networks. The primary side of 33/11kV transformer is modelled by an ideal voltage source at nominal value with the assumption that the primary voltage amplitude is maintained by up-stream OLTC operation.

To test and analyse the OLTC voltage control performance of an 11kV distribution network with DG connection, a series of network models have been developed and implemented by Simulink of MATLAB®. The loads are modelled as constant impedance loads and different types of DG technology have been modelled in detail. However, the equivalent model of a DG comprises one dynamic load block and two gain blocks of Simulink is used for generic simulations to demonstrate the DG impacts on the OLTC voltage control for its simplicity. The dynamic load block can make the equivalent model operate under constant power condition. The gain blocks can make the equivalent model provide or absorb power. If the parameters of the two gain blocks are negative, the equivalent model acts as a DG source. Inversely, if the parameters of the two gain blocks are positive, the equivalent model acts as a load. The impedance of distribution lines has been considered as the equivalent value of an overhead lines and underground cables mixed networks which are obtained by realistic parameters of overhead lines and underground cables from Network Design Manual [125] published by a DNO in the UK. The impacts on voltage control by different X/R ratios of overhead lines and underground cables are demonstrated in one case study when reactive power voltage control is considered.

5.4.2 Case study

5.4.2.1 Conventional OLTC voltage control with AVC relay

The one-line simplified 11kV distribution network shown in Figure 36 is modelled to present voltage profile along the feeder under OLTC voltage control with AVC relay that LDC has not been included. This model consists of a 33kV grid, a 33/11kV transformer equipped with OLTC using AVC relay and a feeder with four loads. The grid has a short circuit level of 1000MVA. The OLTC transformer is rated at 100MVA with 7.5% reactance. The AVC relay deadband was 2% of 11kV. Voltage change per tap is 1.43% with 1 second time delay. The initial tap position is -4 and the reference voltage setting point of AVC relay is 1.05 pu of nominal 11kV. Line impedances and loads are shown in Table 11.

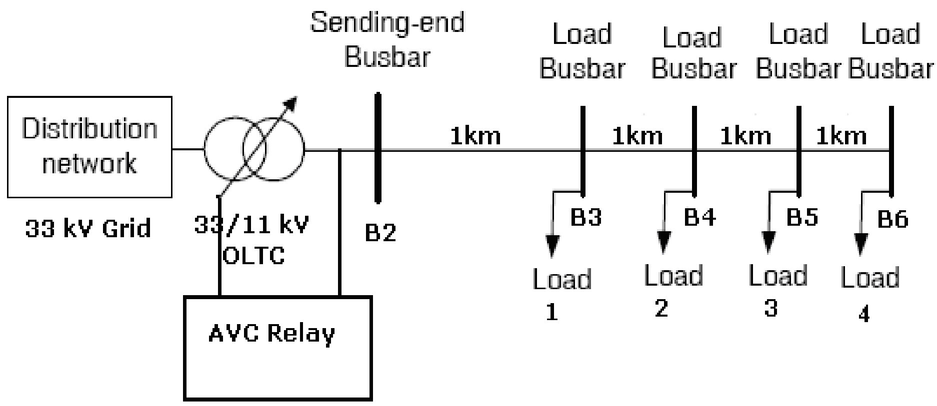


Figure 36. Simplified 11kV distribution network

Table 11. Network data

$V_{network}$	11kV
Resistance	0.76 Ω/km
Reactance	0.35 Ω/km
Load 1	2MW
Load 2	2MW
Load 3	1.5MW
Load 4	1MW

The Simulink model is shown in Figure 37 that the B_2 is sending-end busbar whose voltage is measured to be compared with reference voltage setting point of OLTC with AVC relay. The minimum load condition is that the load 1 and load 2 are both 0.5MW and the load 3 and load 4 are both 0.2MW. The full load condition is shown in Table 11 and 50% load condition is that all of the four loads are half values of full load condition. Three typical network conditions are simulated and the simulation results are shown in Figure 38 as follows.

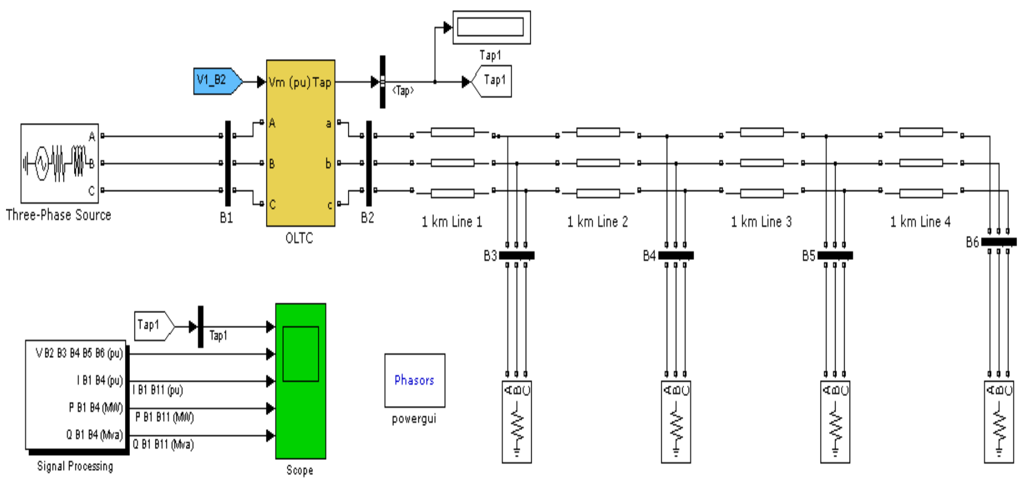


Figure 37. Simulink model of distribution network

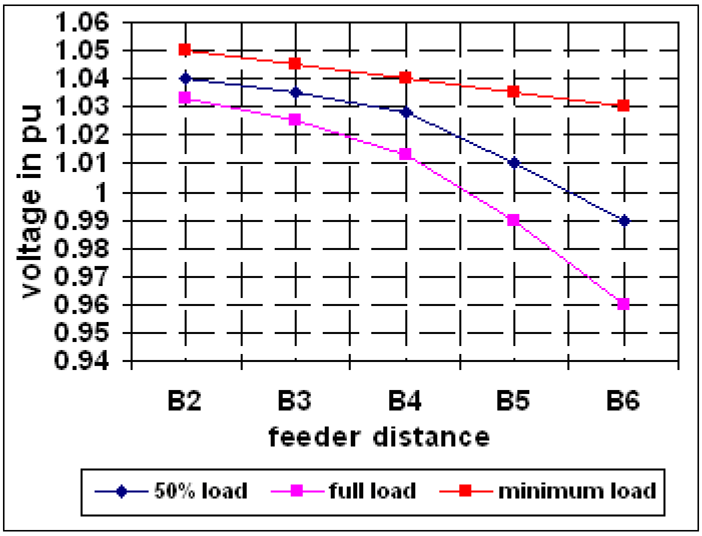


Figure 38. Simulation results of 5.4.2.1

From Figure 38, it can be seen that the voltage profile along feeder in conventional distribution networks is decreased from sending-end busbar to feeder end due to the loads and line impedance. The lowest voltage level (pink line) occurs at the maximum load condition and OLTC with AVC relay can only maintain the voltage of sending-end busbar within the deadband. During the minimum load condition, the voltage along feeder (red line) is higher than the necessary voltage level since the reference voltage setting point is chosen as 1.05 pu. This was chosen to prevent undervoltage under maximum load condition.

5.4.2.2 OLTC voltage control with LDC function

The LDC is applied to AVC relay to realize a remote point voltage control with additional measurement of secondary current of OLTC transformer as Figure 39. The line impedance is simulated as resistance and reactance value by power flow calculation and the voltage drop is created by current across impedance in order to boost the voltage of sending-end busbar. The parameters of the networks are the same as the network in Section 5.4.2.1. The reference voltage setting point for remote point is 1.0 pu in order to keep the voltage along feeder near the nominal value during most of time.

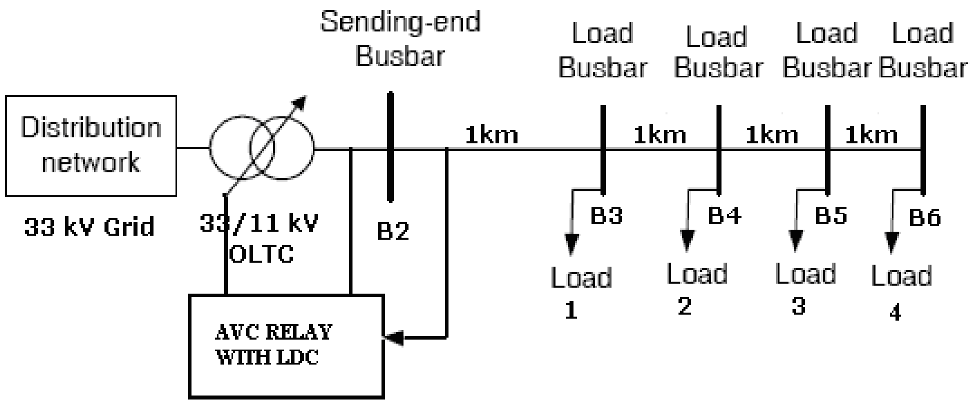


Figure 39. AVC relay with LDC

The Simulink model of OLTC with AVC relay using LDC technique is shown in Figure 40. The LDC setting V_{LDC} has been chosen so that the remote end of the feeder is to be controlled. The initial value of 33kV source is chosen as 1.05 pu and the reference voltage setting point of AVC relay has been chosen as $1.0+V_{LDC}$ pu. The simulation results are described in Figure 41. The OLTC tap operation is controlled by the external LDC control.

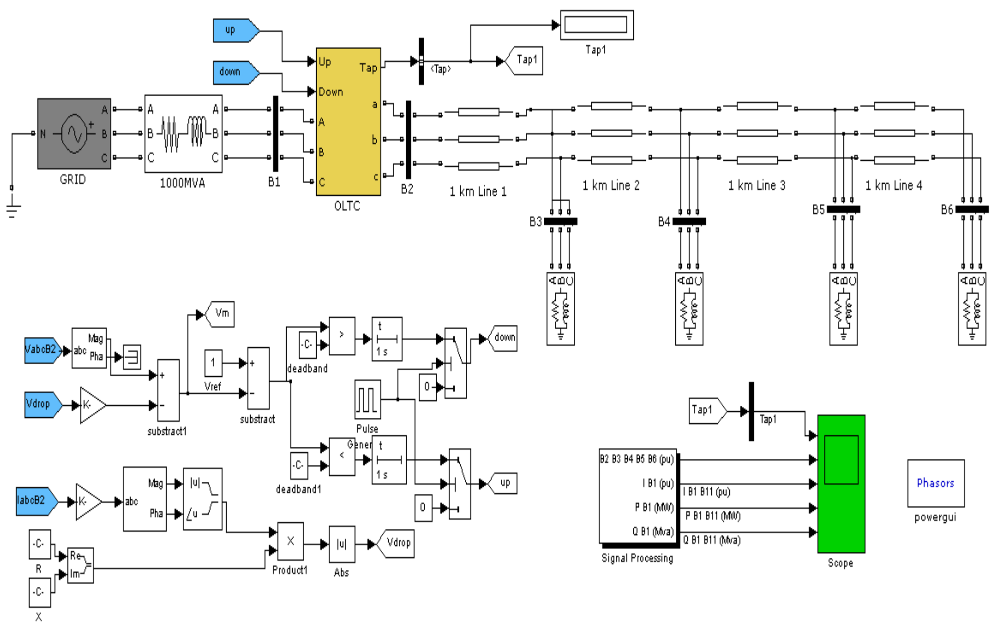


Figure 40. Simulink model of network with LDC

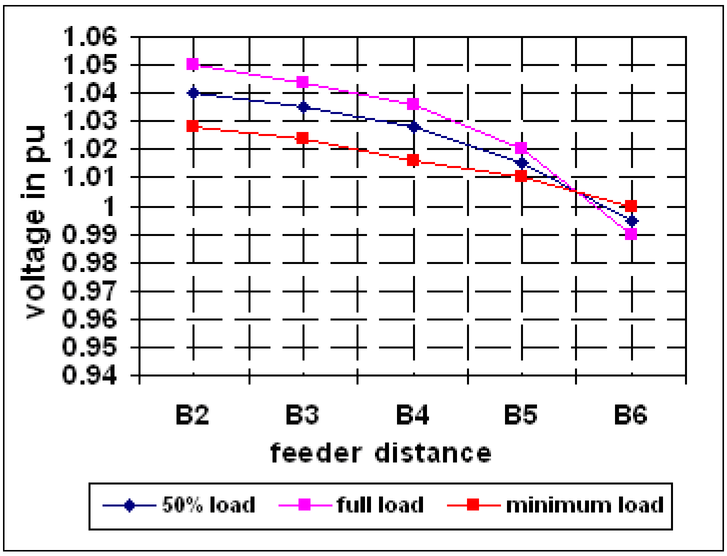


Figure 41. Simulation results of 5.4.2.2

It can be observed that the voltage of remote point (red line) which is end of feeder is maintained within the deadband of nominal value and ensure that the voltage along feeder is not higher than necessary value under minimum load condition. The voltage of sending-end busbar (pink line) is increased by OLTC in maximum load condition in order to avoid the undervoltage situation. The LDC technique can control the voltage of the remote point which is required to be regulated other than the sending-end busbar.

5.4.2.3 Voltage rise with DG connection

The 33/11kV transformer using OLTC voltage control with AVC relays supplies a feeder to which DG and loads are connected along the feeder. The DG is modelled by means of a dynamic load connected to distribution network directly and the equivalent DG model represents one or more generators at the same node. Due to the high degree of intermittent nature of renewable resources, DG and loads which make use of renewable energy are characterized as uncertain factors hence the different DG outputs under different load conditions are simulated to demonstrate the impacts on conventional OLTC voltage control. The parameters of network are the same as Section 5.4.2.1 and DG is connected at bus B_4 whose capacity is 10MW with unity power factor. The network is shown in Figure 42. The maximum generation, half generation and light generation of DG is 10MW, 5MW and 1MW respectively. The reference voltage setting point of AVC relay has been chosen to be 1.04 pu in order to transmit power from substation to load.

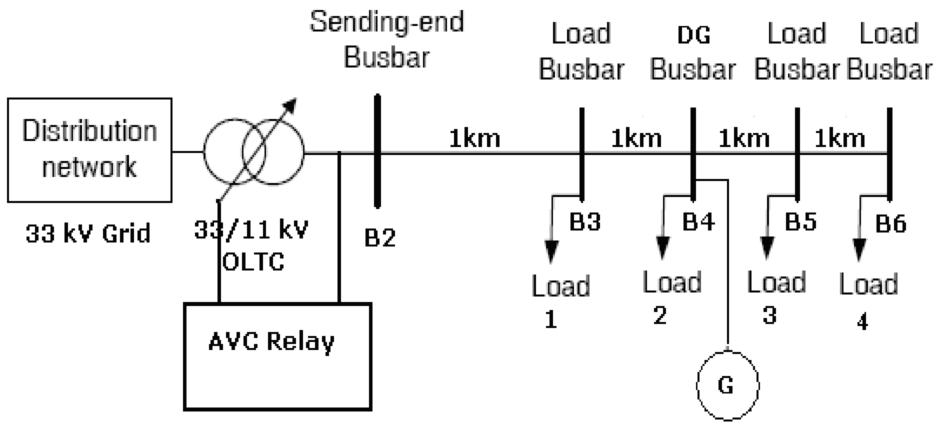


Figure 42. Distribution network with DG connection

The 11 kV distribution network is modelled in Simulink as Figure 43.

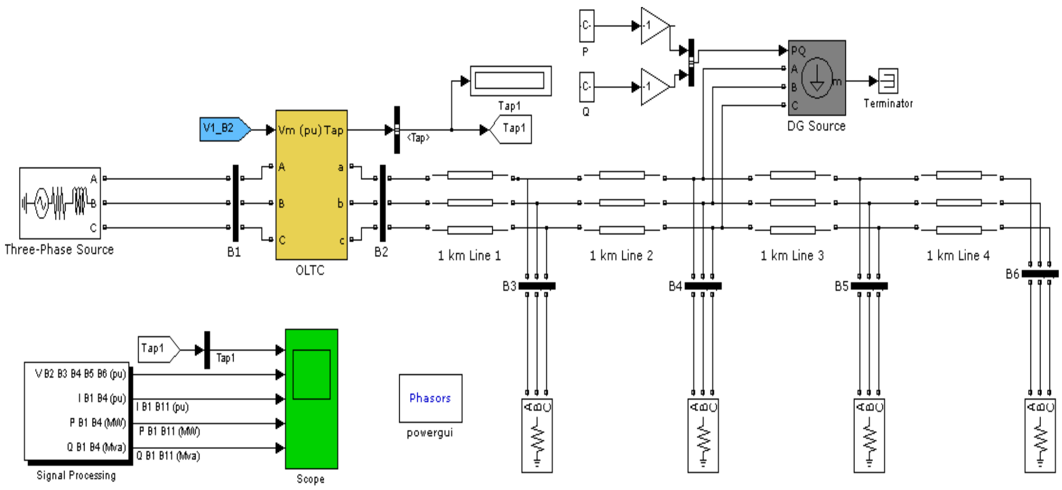


Figure 43. Conventional OLTC voltage control with DG

The voltage profile of network at buses B_2 to B_6 under AVC relay influence has been simulated with DG integration. Figure 44, 45 and 46 show the voltage performance of conventional AVC relay with various DG output under different load conditions.

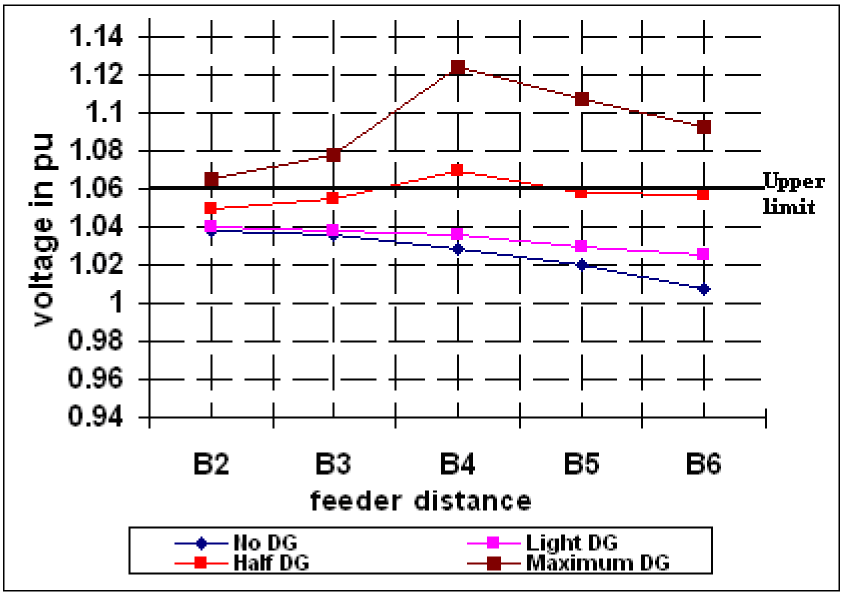


Figure 44. Voltage profile with DG under minimum load condition and varying levels of generation

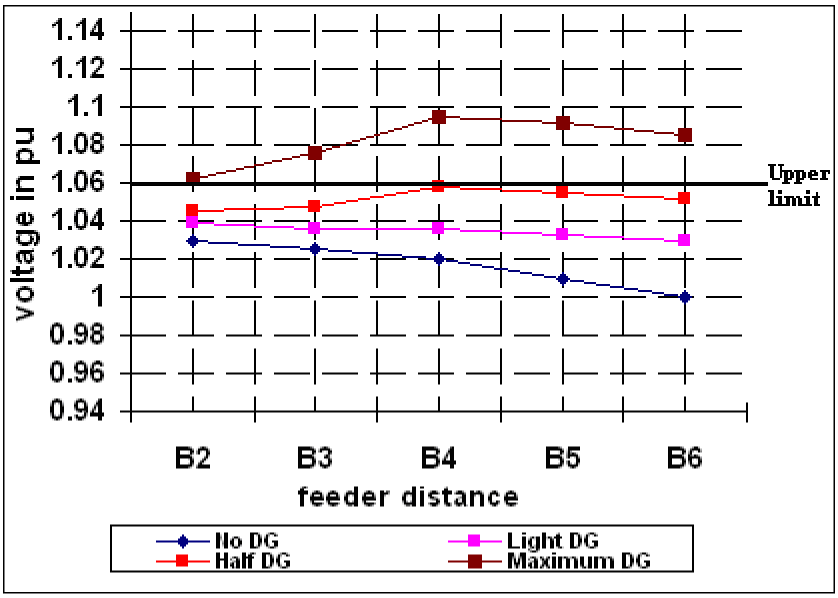


Figure 45. Voltage profile with DG under half load condition and varying levels of generation

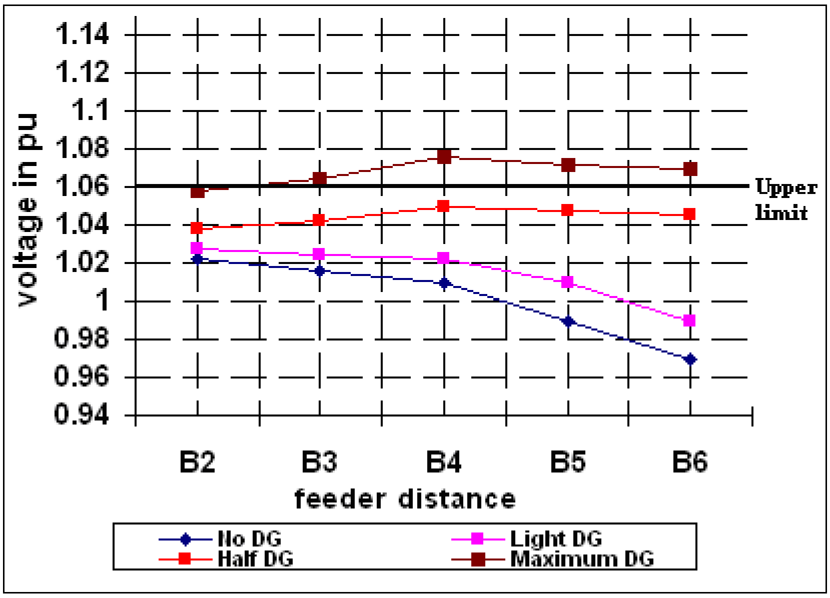


Figure 46. Voltage profile with DG under maximum load condition and varying levels of generation

In Figure 44, it can be seen that the voltage level (blue line) is decreased from the sending-end busbar to feeder end due to the line impedance when there is no DG. The impact of light DG is acceptable that the voltage level (pink line) of connection point is rise a little but not significant under all of the load conditions. When DG is half (red line) and full generation (brown line), the voltage of connection point is rise dramatically and caused overvoltage especially under minimum load condition. Since the conventional AVC relay only measures the sending-end busbar voltage and maintain it within an acceptable range. No voltage information of the feeder is provided at other busbars and in cases of large DG connection voltage of some points is out of limits, even with operation of AVC to keep the terminal voltage.

5.4.2.4 Reversed power flow with DG connection

The LDC technique is often employed as a more sophisticated method to control OLTC by some DNOs in HV distribution networks. The LDC method used the measured secondary current of OLTC transformer to compensate for voltage drops in the feeder to stabilize the voltage at a load. The change of power flow caused by DG integration into networks results in uncertainty in LDC operation due to the possible reversed power flow condition when DG output is larger than loads. The network model using LDC technique with DG connection is shown as Figure 47 to demonstrate the impacts on LDC technique by the reversed power flow.

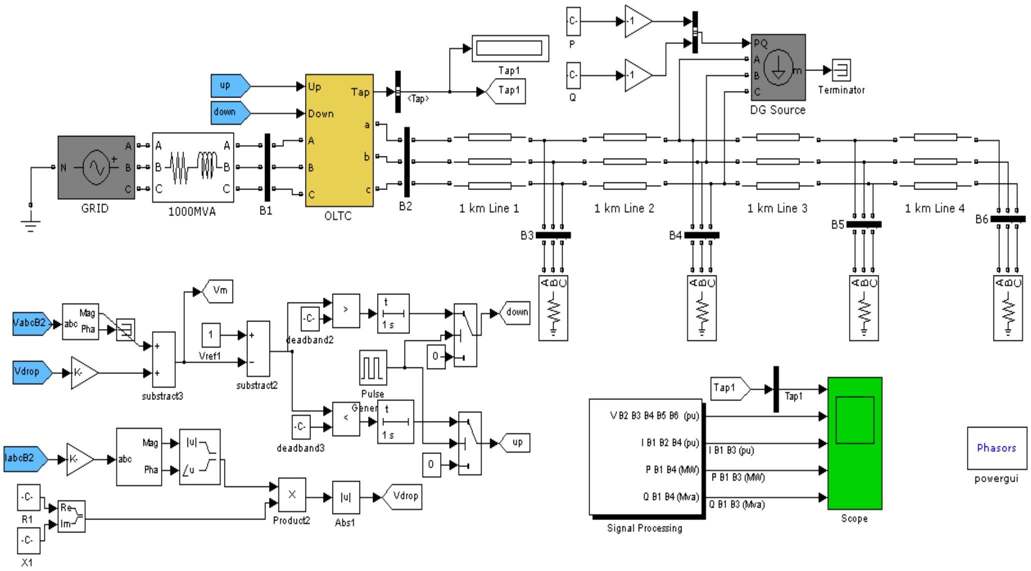


Figure 47. AVC relay using LDC technique with DG

In minimum load condition, the sending-end busbar voltage is low when LDC is used. The reversed power flow problem caused by DG penetration is less clearly than that under the maximum load condition because the voltage along the feeder is higher under maximum load condition which can illustrate the impact more obviously. Therefore the maximum load condition is considered in this simulation and DG output is chosen as 8 MW which reversed the power flow to show impacts of reversed power flow on LDC technique as Figure 48. The reference voltage setting point of AVC relay is 1.0+V_{LDC} which is 1.03 pu in the following simulation case.

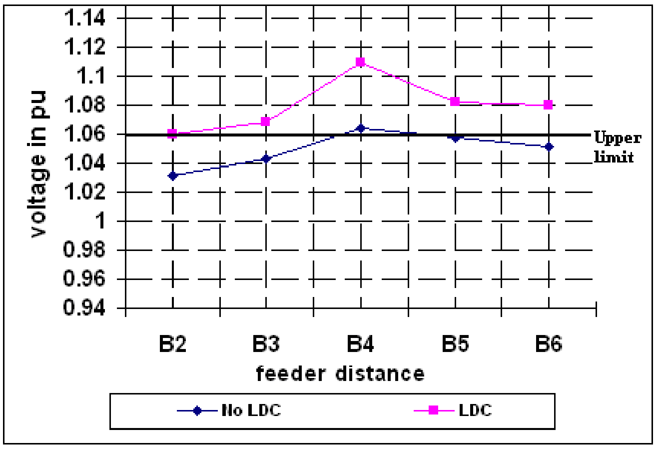


Figure 48. LDC under reversed power flow

From Section 5.4.2.2, it can be seen that LDC can provide remote control to maintain the feeder end voltage instead of the sending-end busbar voltage at the set level. The voltage control performance is better than conventional AVC relay without LDC when there is no DG connection. When DG power output is larger than load demand, then the power flow is reversed and the LDC is inaccurate as Figure 48. The measured current value is used in LDC without consideration of power flow direction and assumes that it is flowing down the feeder. The voltage rise along feeder has been seen as voltage drop by LDC hence LDC operates the OLTC to tap up in order to increase the sending-end busbar voltage to compensate the apparent voltage drop. The voltage rise problem at the DG connection point is worsened. When the power flow is reversed, the LDC makes the voltage control performance worse than conventional control without LDC thus it is seen to be inadequate to control the voltage.

5.4.2.5 Impact of X/R ratios of overhead lines and underground cables

In the traditional view of power networks, power flow is only in one direction, from transmission networks to distribution networks via substations and then to loads. With DG penetration, the voltage drop on the one feeder network can be approximated as equation (10) rewritten by:

$$\Delta V = V_S - V_L \approx \frac{R_L(P_L - P_{DG}) + X_L(Q_L - (\pm Q_{DG}))}{V_L} \tag{14}$$

where P_L, P_{DG}, Q_L, Q_{DG} are active and reactive power of load and DG respectively, R_L, X_L are the line impedance, V_S, V_L are the sending-end busbar voltage and load busbar voltage respectively. Q_G is positive value when the DG exports reactive power and negative value when the DG imports reactive power.

The reactive power absorbed by DG can use the $X_L(Q_L + Q_{DG})$ to compensate the $R_L(P_L - P_{DG})$ in order to reduce voltage rise problems. The performance of reactive power for voltage control is different according to the various X/R ratios of 11kV overhead line and underground cable. The model of Figure 43 is used to simulate the voltage control under network using overhead lines and underground cables separately to test the X/R ratio impact. The typical parameters of 11kV overhead lines and underground cables are given in Table 12. The active power exported of DG is 3MW and reactive power absorbed is 4Mvar under the minimum load condition to demonstrate the impact of X/R ratio in the following simulation case study.

Table 12. Data of 11kV distribution lines

	Conductor		Resistance	Reactance	X/R ratio
11kV overhead line	Size	Type	R (Ω/km)	jX (Ω/km)	
	$50mm^2$	AAAC Hazel	0.550	0.351	0.64
11kV underground cable	Cable		Resistance	Reactance	X/R ratio
	$70mm^2$	AI Triplex	0.443	0.125	0.28

The simulation results are shown in Figure 49, from which it can be seen that the reactive power imported by DG can be used to reduce the voltage rise and the efficiency depends on the X/R ratio of distribution lines and amount of active and reactive power. The X/R ratio of overhead line is much larger than underground cable thus the reactive power for voltage control has a better performance.

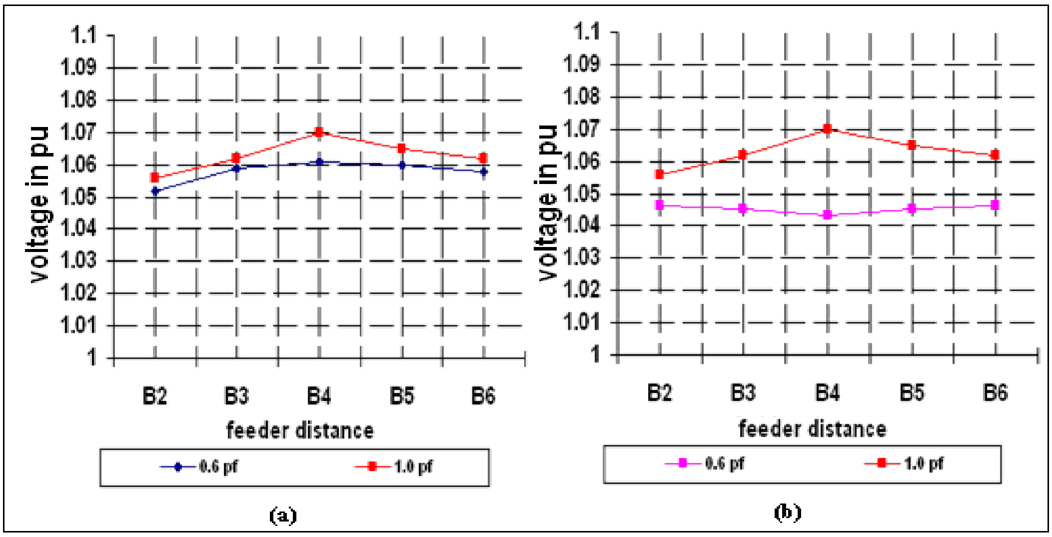


Figure 49. Reactive power control
(a) Underground cable, (b) Overhead line

When the DG power factor is 1.0, the voltage profile (red line) of underground cable network is nearly the same as the voltage profile of overhead line network which are shown in Figure 49 (a) and (b).

From the Table 12, it can be seen that the X/R ratio of overhead line about 0.6 in distribution networks is much smaller than that about 10 in transmission networks. Therefore using the reactive power absorbed by DG for voltage control is inefficient in distribution networks. Typically a DG using synchronous generator can absorb reactive power at 0.95 power factor and wind turbine using asynchronous generator at about 0.9 power factor without external compensation device due to the network charging mechanism. If the DG reactive power imported is involved in voltage control, the cost of reactive power purchase and its impact on the network must be considered by both DNO and DG owner. Additionally, a significant reactive power flow can impact on the losses and load in distribution networks. The reactive power effect for voltage control is much lower in magnitude than the active power due to the low level of X/R ratio of 11kV distribution networks thus the reactive power voltage control has been neglected in this research. The resistance of distribution line and active power are the dominant factors for voltage control in distribution networks. Since the typical resistance values of different lines are similar for 11kV networks by Network Design Manual published by a DNO in the UK. Therefore the line impedance parameters in the following simulations which using underground cable, overhead line or mixed line are mainly considered as similar influence when only active power is exported by DG.

5.4.2.6 Different DG technology impact

5.4.2.6.1 Synchronous generator DG

A synchronous machine model is used to connect distribution network directly to represent synchronous generator type DG. The synchronous generator is connected at the remote end of the feeder and is operating at a power factor of 1.0 and the voltage of generator terminal is not controlled with pf-control exciter system under the generator model mask in Figure 50. The parameters of networks are the same as Figure 43 and the power of synchronous generator is 10 MW under maximum load condition.

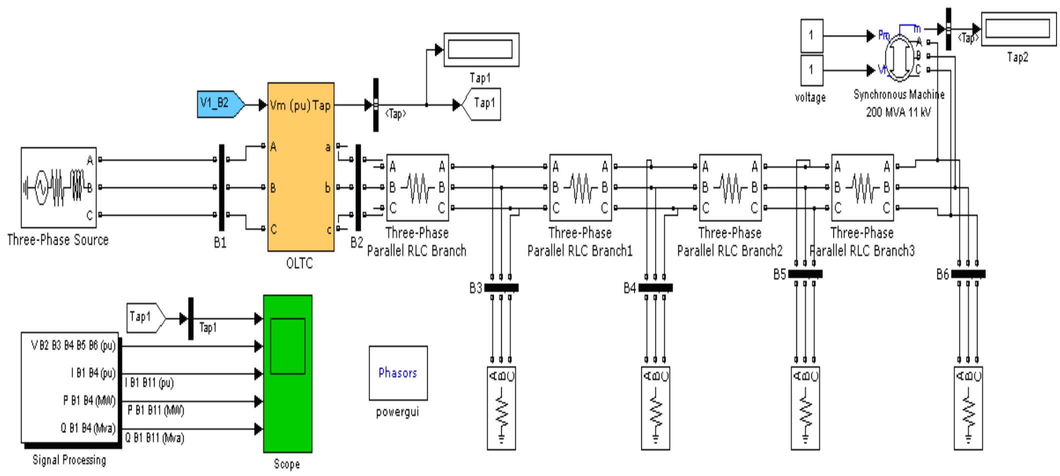


Figure 50. Synchronous generator DG

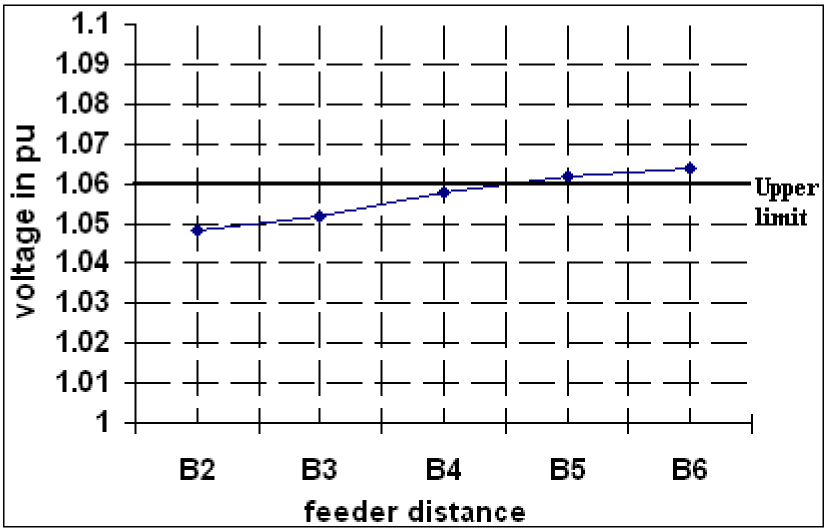


Figure 51. Voltage profile of network with synchronous generator

The voltage profile of the network with a synchronous generator is shown in Figure 51. The performance of synchronous generator is similar to that of the equivalent dynamic load DG when only voltage is considered in the networks.

5.4.2.6.2 Asynchronous generator DG

A 9MW wind farm is connected to an 11kV distribution network to export power through a 5km overhead line as Figure 52. The wind farm consists of six 1.5MW wind turbines. The wind turbine use DFIG and the power electronic converters have the ability to import or export reactive power thus the external reactive power compensation devices are not required. The wind speed is set as 16m/s to ensure the high speed for asynchronous generator with 9MW output power at 0.9 power factor to absorb reactive power under half load condition that all of the loads have the 50% value of full load value which are given in Table 11. The overhead line data is also the same as Table 11. The simulation result is shown in Figure 53.

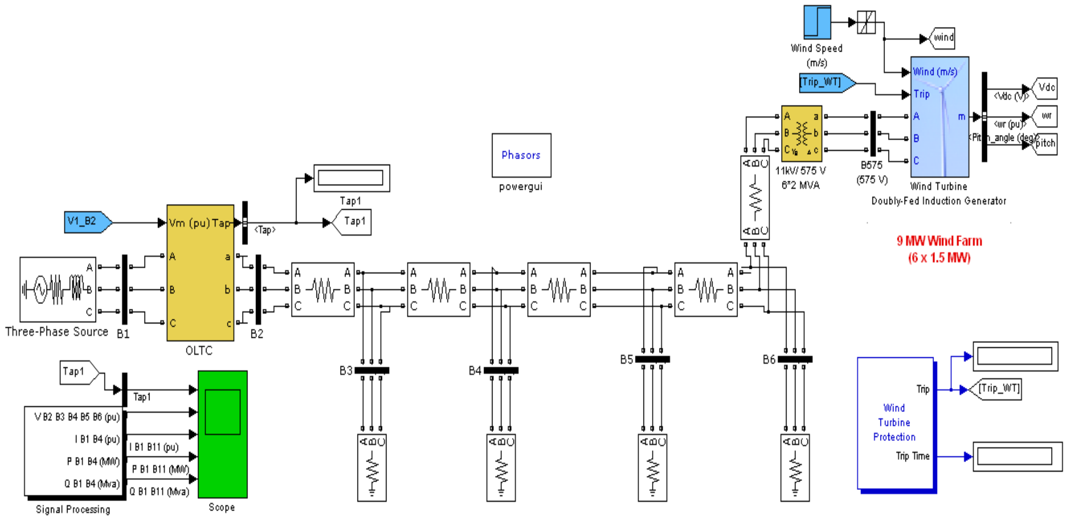


Figure 52. Wind farm connected to distribution network

The initial voltage of sending-end busbar is 1.03 pu and the OLTC is controlled by conventional AVC relay without LDC. The reactive power absorbed by wind farm is about 4.36Mvars. The distance between B_6 busbar and B_{575} busbar is 5km.

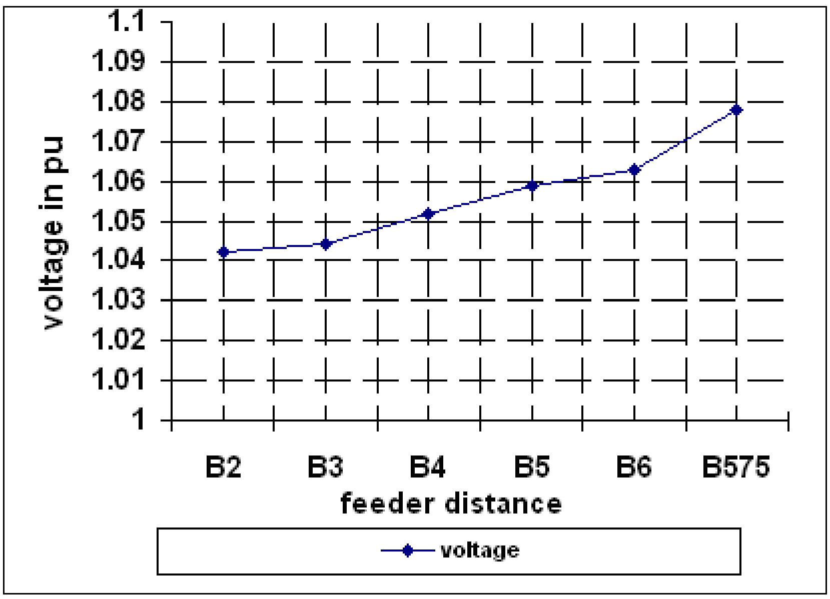


Figure 53. Voltage profile with wind farm connection

From Figure 53, it can be observed that the voltage level of wind farm is over the voltage limit since the voltage rise along the long overhead line is large when wind farm has generated a large amount of power. The amount of reactive power absorbed by wind farm is smaller when compared to its active power output and low X/R ratio of distribution network has little effect on the voltage profile.

5.4.2.6.3 Inverter-based DG

The model of a Solid Oxide Fuel Cell (SOFC) is connected to an 11kV distribution network through an IGBT inverter which is utilized in SimPowerSystems™ [147] as Figure 54. The active power is controlled by hysteresis switching while the reactive power is maintained at zero. The SOFC rated at 0.5MW and the load condition is minimum load. The Figure 55 presents the voltage profile along the feeder.

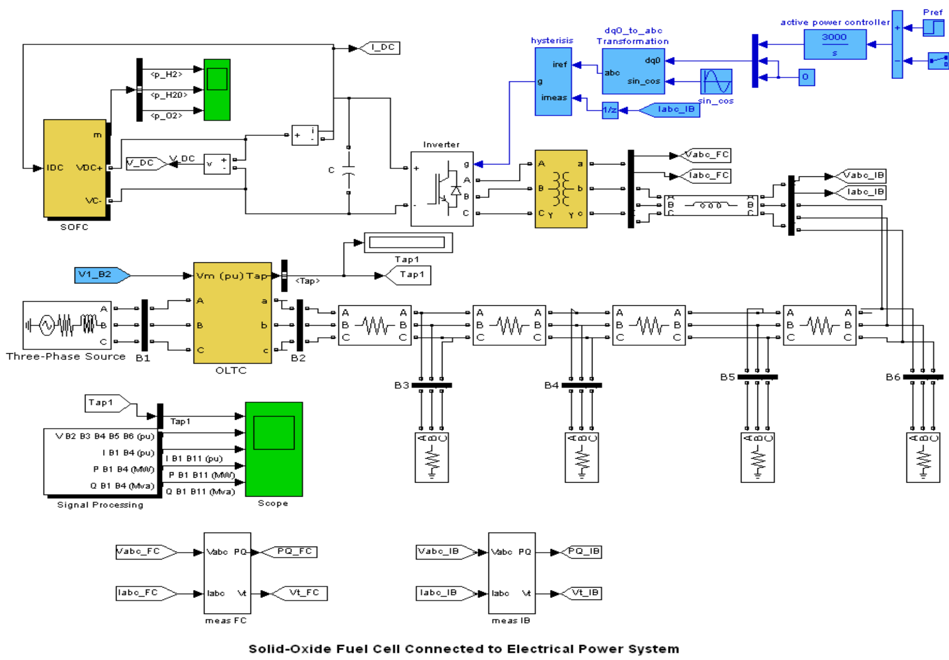


Figure 54. SOFC connected to distribution network

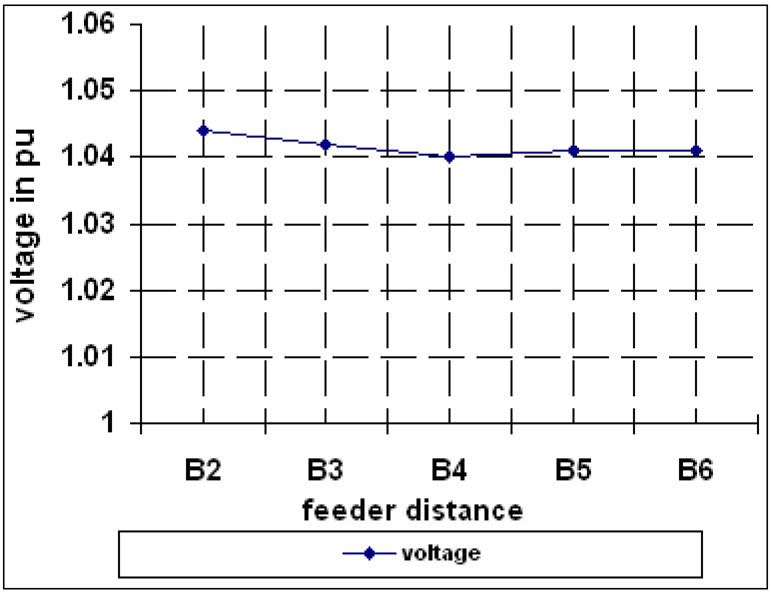


Figure 55. Voltage profile of SOFC connected network

The inverter-based DG such as solar PV and SOFC generally has small power output with unity power factor to reduce peak load demand or supply the minimum load condition. The voltage rise problem is not significant for this type of DG in distribution networks as Figure 55 if only the output power is considered. Nevertheless the power output can reach a high level if a number of PV arrays or fuel cells are combined together, it is impractical to implement due to the high cost and relevant technical problems of connection, control and operation.

5.4.2.7 Worst case operation policy from DNOs

The impacts of DG on voltage profile with OLTC voltage control depend on DG power, location, line impedance and load conditions. An 11kV distribution network shown in Figure 56 is modelled and the line impedance per kilometre is increased from the sending-end busbar to the end of feeder in practical distribution networks since loads tend to become smaller and therefore DNOs use conductors of decreasing cross-sectional area [130]. When DG is connected to network, the DNO applies the worst case scenarios as the operation policy to guarantee the network is not affected according to the ESQC. The minimum load condition is always assumed as no load produces the worst scenario by some DNOs [127].

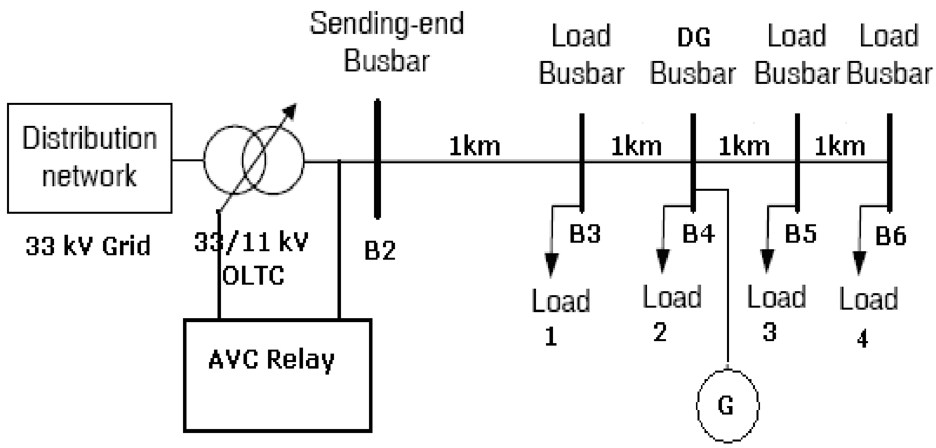


Figure 56. Single line diagram

The parameters of distribution lines and loads are list in Table 13.

Table 13. Network parameters

$V_{network}$	11kV
B2-B3 Impedance	0.06 + j0.05
B3-B4 Impedance	0.14 + j0.11
B4-B5 Impedance	0.28 + j0.20
B5-B6 Impedance	0.58 + j0.40
Load 1-Load 4	1MW

Without any DG connected, the voltage drop is increased towards the feeder end due to the higher line impedance although the loads are equal as shown in Figure 57 under the maximum load, no DG generation condition. In order to avoid the undervoltage of load at the feeder end, the voltage of sending-end busbar is chosen as 1.04 pu for the worst case scenarios.

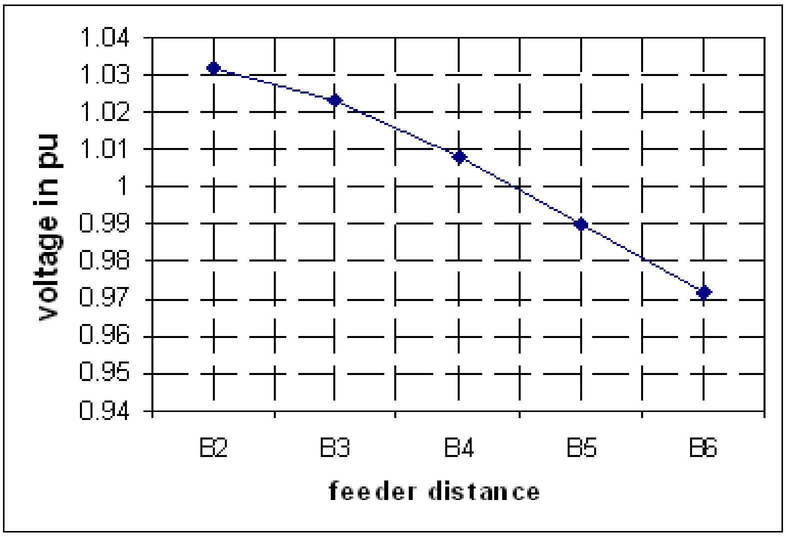


Figure 57. Voltage profiles under no DG condition

With a DG connected to bus B_4, the impact of small DG can be acceptable and the voltage level of connection point will raise little if the power output is small. In Figure 58 below, if the power output is 5MW, under maximum load condition, the voltage level is still within statutory limits. When DG output power is increased above 5MW, the voltage level (blue line) of DG connection point will rise further and cause overvoltage. In the case shown in Figure 58, DG would have to reduce the output to less than 5MW to ensure the voltage levels (pink line) along feeder are within required limits. If the minimum load condition is considered, the output power of DG must be further reduced to 1MW representing the minimum load, maximum generation scenario.

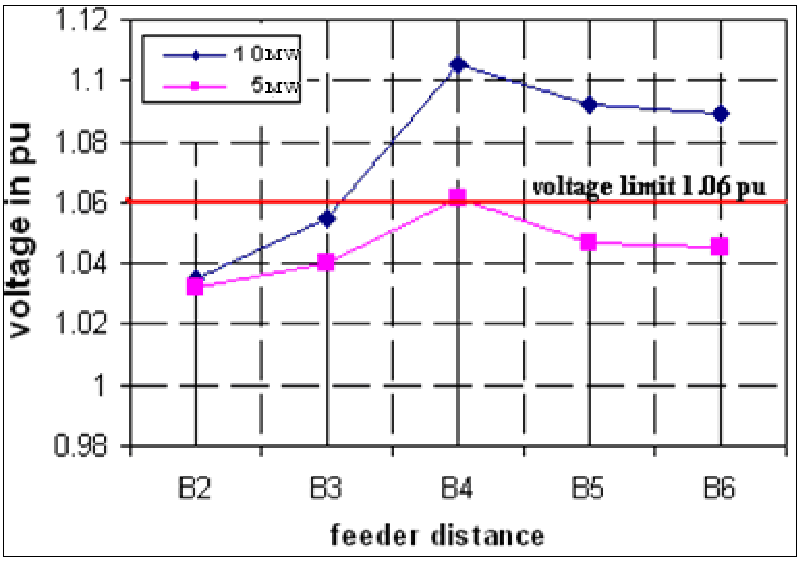


Figure 58. Voltage profiles with maximum load

The worst case scenarios operation policy by DNOs can only allow 1MW DG to be connected to the network in the above simulation case study in order to ensure the network is continually operating without causing overvoltage. Therefore, this is a significant constrain has been applied to the DG capacity that can be connected to a distribution network.

5.5 Current OLTC voltage control technique developments

5.5.1 The Enhanced TAPP scheme [37]

The Enhanced TAPP scheme operates efficiently to parallel transformers and maintain appropriate tap positions for all OLTCs under varying power factor across the networks without the degradation of LDC performance is presented by M. Fila and G. Taylor. The drawbacks of the basic schemes associated with power factor deviation are eliminated. Even the voltage profile of distribution networks can be improved by

Enhanced TAPP scheme when the DG output is limited.

The paralleled transformers of Enhanced TAPP scheme can be on the same site or at different locations in network since this scheme combines True Circulating Current scheme and TAPP scheme to accommodate the two situations respectively. The Enhanced TAPP scheme is based on TAPP scheme and the True Circulating Current scheme in Section 2.5.2 and Section 2.5.4 is added to the TAPP controllers in order to paralleled OLTCs on the same site which is shown in Figure 59.

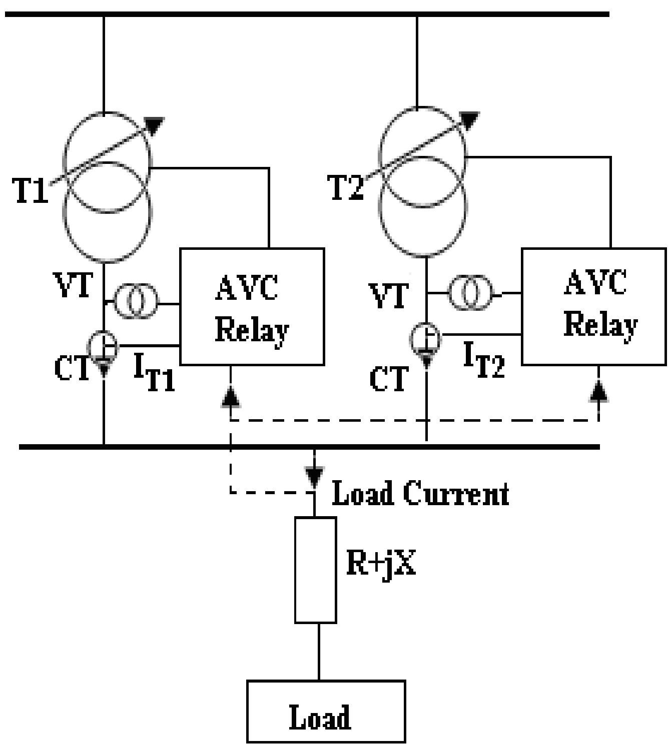


Figure 59. The Enhanced TAPP scheme diagram

In the True Circulating Current mode, the measured transformer current I_{Tn} and load current I_{T1} + I_{T2} are used to calculate the circulating current by equation (15).

$$I_{CIRT} = \frac{I_{T1} - I_{T2}}{2} \tag{15}$$

The AVC relay measures the increased target voltage with higher tap position and decreased target voltage with lower tap position due to the compounding voltage bias ($I_{CIRT} \cdot Z_T$). Then a tap down action for OLTC transformer on higher tap position and a tap up action for OLTC transformer on lower tap position are operated until the circulating current is minimised.

The Enhanced TAPP scheme can use the LDC which the group load current (I_{T1} + I_{T2}) is employed to provide a LDC voltage boost as the follow equation (16):

$$V_{LDC} = \sum_{n=1}^{T} I_{Tn} \cdot \left(R_{LDC} + jX_{LDC}\right) \tag{16}$$

where T is the number of transformers which are feeding the local network. When the paralleled OLTCs are across the networks, the TAPP mode is implemented that the circulating current is calculated by summed load current and target power factor as the principle is described in Section 2.5.4. The detail simulations is demonstrated and analysed in [37].

The drawback of this scheme is that power factor deviation can cause voltage error when the TAPP mode is used when the parallel transformers across the networks therefore it is unsuitable for large amount of DG connection. The overvoltage problem caused by DG integration is unable to be solved since the LDC function is inaccurate with DG connection as described in Section 5.2, thus the capacity of DG that can be supported is limited.

5.5.2 SuperTAPP n+ relay

Fundamentals Ltd introduces the new scheme SuperTAPP n+ relay which is based on Enhanced TAPP scheme [148]. This relay is used Enhanced TAPP principle to parallel OLTC transformers and an additional estimation technique is employed to control the voltage of DG connection point. Simulations have shown that the parallel performance is not influenced by DG integration with Enhanced TAPP voltage control scheme. The SuperTAPP n+ relay can estimate current output I_G of DG by using the additional current measurement I_{FG} on feeder 1 with DG and load share ratio E_{ST} which presents the load share between feeders with DG to those without DG as shown in Figure 60. The ratio is calculated when the DG is not connected.

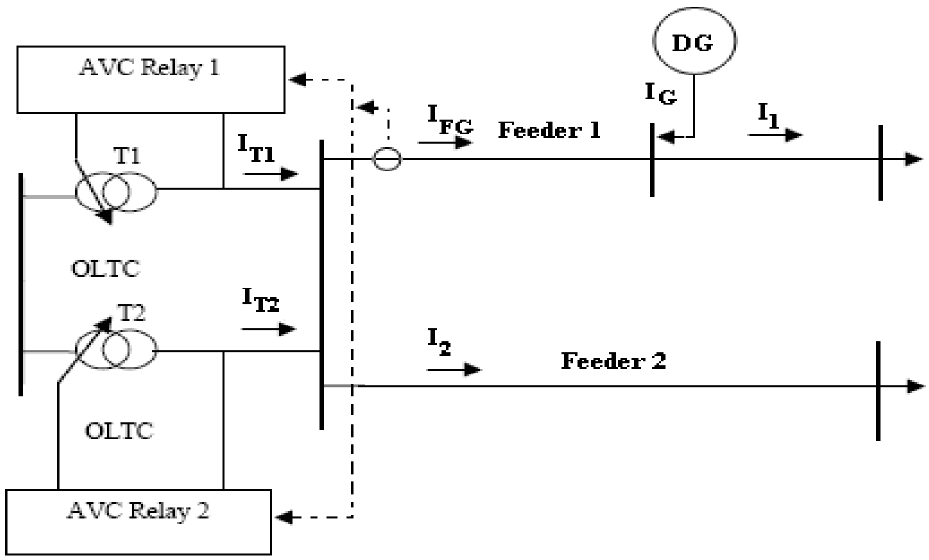


Figure 60. SuperTAPP n+ relay scheme

Where I_G is calculated as follow equations:

$$E_{ST} = \frac{Load \ \ on \ \ feeder \ \ with \ \ generators}{Load \ \ on \ \ feeder \ \ without \ \ generators} = \frac{I_1}{I_2} = \frac{I_{FG}}{I_{TL} - I_{FG}} \tag{17}$$

$$I_{TL} = \sum_{n=1}^{T} I_{Tn} = I_{T1} + I_{T2} \tag{18}$$

$$I_G = (E_{ST}(I_{TL} - I_{FG})) - I_{FG} \tag{19}$$

where the voltage rise at connection point can be evaluated that the proper generator compensation bias V_G can be determined as follows

$$V_G = V_{GMAX}\% \frac{I_G}{I_{GMAX}} \tag{20}$$

This is applied to AVC relay to calculate the effective voltage setting to control the voltage profile in network with DG. Detailed case studies and software simulations are presented in [148]. The simulation results confirm that the improved performance of the new technologies is adequately to accommodate DG while the DG capacity is increased from 2MW to 3MW in one case study and 3.8MW to 6MW in another case study. Because all measurements are local measurements without communication and the true load current is used in LDC therefore this method can provide an accurate performance. However, this scheme is inaccurate when different feeders containing more than one DG. The I_G is unavailable to be estimated since a suitable load share ratio for every DG feeder is unable to be selected. When the DG and network conditions are complex, the performance of this method is not satisfactory any more. The SuperTAPP n+ scheme requires at least one feeder without DG connection because the voltage estimation in this scheme is highly depended on the accuracy of load share ratio. When the deviation of the load share ratio is in the range of 20%, the voltage estimation error is 70%.

5.5.3 Coordination control of STATCOM and OLTC

The Static Synchronous Compensator (STATCOM) is a Flexible AC Transmission Systems (FACTS) device. With the development of power electronic devices for transmission networks, they are also being applied to distribution networks. STATCOM regulates voltage by using reactive compensation to control power flow. Due to the fast response, STATCOM provides the opportunity to improve power quality and reliability and has the functional capability to handle dynamic conditions in addition to provide voltage regulation [149]. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from power grid. When system voltage is low, the STATCOM injects reactive power to the network. When system voltage is high, it absorbs reactive power from the network.

M. Khederzadeh presents a coordination control strategy in paper [150] to limit the steady-state reactive power output of STATCOM based on an OLTC voltage control scheme. Figure 61 shows the test system of the controller in Simulink.

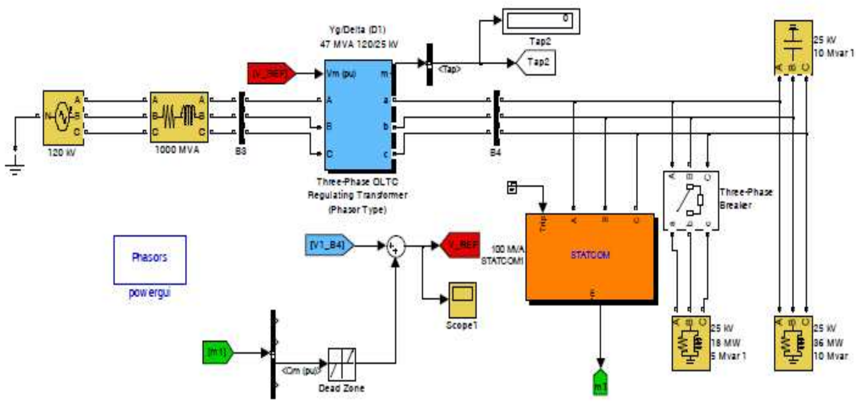


Figure 61. OLTC coordinated with STATCOM [150]

With variable load, the STATCOM generates or absorbs required reactive power and quickly keeps the voltage of load bus at certain value, and therefore stabilize it at a steady-state operating point. The coordination controller activates the OLTC and sets tap at a position with nearly zero STATCOM output. When STATCOM output is nearly zero, the reference voltage setting point is the load busbar voltage. Otherwise, the voltage setting point is higher or lower than the load busbar voltage. The OLTC is operated in order to compensate the reactive power already supplied by STATCOM. By each tap changing, STATCOM decreases its output thereby the final voltage setting point reaches the load busbar voltage as required [150]. However, the expensive and low efficiency of this coordinated control method in HV and LV networks result in that it cannot be used in practical operation.

5.5.4 GenAVC system

State Estimation (SE) is used in a commercial GenAVC system with communication as shown in Figure 62. Remote Terminal Unit (RTU) is installed at each strategic location in distribution networks to monitor the voltage and power flow. The real-time measurements are transited to SE in substation via available communication networks. The network data is also provides to SE with the real-time measurements to estimate voltages throughout the network therefore determining a suitable reference voltage setting for the OLTC transformer with AVC relay [151].

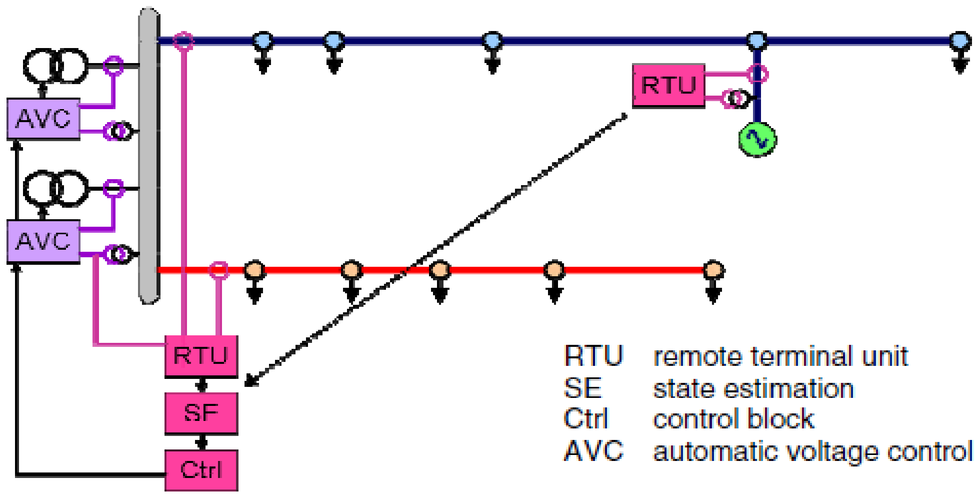


Figure 62. Implementation of GenAVC system [151]

The simulation results from [151] show that the DG capacity is increased from 2MW to 3MW by using GenAVC methods. The limitation of this method is the high cost due to the installation and operation of RTUs and communication links. Another limitation is that the SE requires static network model for accurate estimation. When the abnormal configuration of network occurs due to additional connections, the GenAVC system has to be disabled to modify the network model since the estimation model is uncoordinated with the real-time network state. The efficiency of this method is highly depending on the availability of communication network and accuracy of estimation.

5.5.5 Automatic Voltage Reference Setting (AVRS) technique

H. Leite and H. Li proposed an AVRS technique which is an OLTC control algorithm that provides suitable reference voltage setting point for AVC relay dynamically using RTUs and SE. The voltage of two or more essential points along the multiple feeders from one substation are measured by RTU and transited to AVRS device via communication networks as shown in Figure 63 [152].

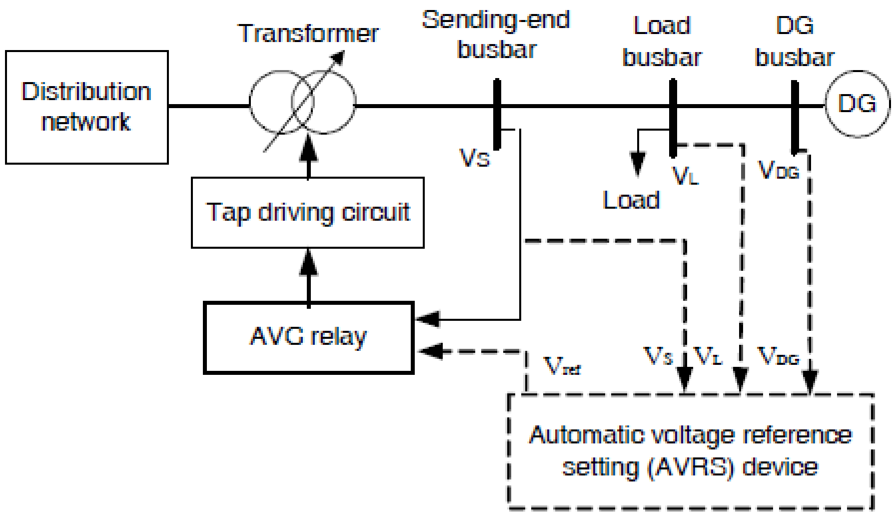


Figure 63. Distribution network with AVRS technique [152]

The maximum and minimum voltage values are obtained from the measurements to compare with the statutory limits. Then a new reference voltage setting for AVC relay is determined according to the flow chart in Figure 64 to maximise the DG capacity connected in the distribution network. The simulation results show that the AVRS algorithm can be used for OLTC voltage control while increasing the DG capacity from 200kW to 1600kW under minimum load condition and from 100kW to 2100kW under maximum load condition [152].

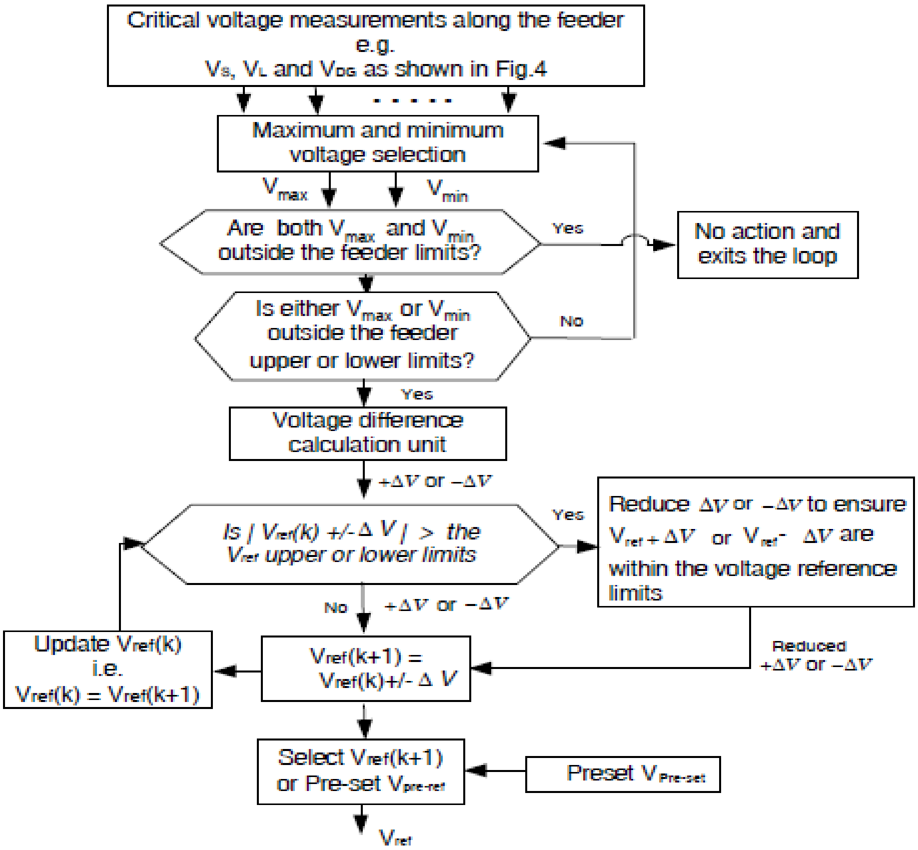


Figure 64. Flow chart of AVRS algorithm [152]

5.6 Summary

The integration of DG results in the basic simplifying assumption used by conventional voltage control in distribution network to be invalid. To maintain the voltage of all loads within certain limits and overcome the restriction placed on DG capacity, DNOs require a more active voltage control algorithm that can be adopted for the short-term or medium-term distribution network conditions without significant reinforcement. New OLTC control methods are required to overcome these limitations and accommodate the demands of modern power systems.

Chapter 6

Advanced compensation-based OLTC voltage control algorithm

This chapter presents an advanced compensation-based OLTC voltage control algorithm in distribution network with DG connection. It starts with the improved Automatic Compensation Voltage Control (ACVC) technique which has a better performance than conventional LDC when DG is connected. The simulation case of ACVC operation compared with LDC in Simulink is included. Then the advanced compensation-based OLTC voltage control is proposed.

6.1 Introduction

The voltage control in distribution networks is mostly implemented by OLTC with an AVC relay and the widespread use of OLTC is likely to continue as the primary voltage control for many decades to come. The DNOs design OLTC voltage control policy that determines the voltage of transformer secondary side according to load condition to maintain it within the statutory limits. This voltage control policy based on simple constant voltage of OLTC is particularly designed for passive distribution networks where the power flow is unidirectional from substation to the feeder end. A high level of DG penetration into distribution networks results in the bidirectional power flow and voltage rise thus the existing

OLTC voltage control methods are essentially inadequate to support DNOs. The voltage rise problem caused by DG and inaccurate LDC due to reversed power flow are the main factors for the limitation of DG capacity that DNOs must take the worst case scenarios into account in supplying the power to all of customers.

The voltage rise caused by DG connection can be controlled by OLTC to lower the secondary voltage when DG output is high. In order to obtain maximum power exported from DG, it is necessary to reduce the voltage of sending-end busbar while ensuring that the voltage of load centre in other no DG feeder end is above the lower voltage limit. However, an undervoltage is most likely to occur if the DG is disconnected when there is a heavy load on the feeder. The load centre voltage at the end of other feeders which without DG are likely to drop below the lower permitted voltage limit. The intermittent nature of renewable energy resources lead to that the voltage of sending-end busbar must be controlled dynamically with knowledge of the feeder state to ensure that every node voltage along different feeders is within the statutory limits.

The ideal real-time measurement of network states can guarantee a satisfied voltage control for DNOs. Remote Terminal Units (RTUs) as used in GenAVC [153] is one example to provide voltage information of remote points to substation control system by license-free directional radio communication. However, the real-time voltage control highly depends on the communication system which is not generally available for distribution networks and the cost is expensive since the monitoring level of existing distribution network is extremely low thus a large amount of monitoring equipment needs to be installed to achieve the real-time voltage control.

DNOs are facing many challenges in control of their systems due to the number of DG connection in distribution network is growing significantly. Voltage control is identified as the main factor to limit the DG penetration into HV distribution networks. Since OLTC transformer is the main voltage control device in HV distribution networks, a cost-effective method is required by DNOs to provide a reliable OLTC voltage control to maintain the voltage while increasing DG capacity in distribution networks. The proposed OLTC voltage control algorithm is presented in this thesis to provide an improved voltage control performance with DG penetration. The objective of this control algorithm is to supply a reliable voltage control while enabling the maximum DG capacity in order to bring the largest benefits from the DG point of view and increase the utilisation of the existing distribution networks. This advanced compensation-based OLTC voltage control using ACVC technique depends on the power flow direction, load pattern and DG location to estimate voltage drop or voltage rise therefore selecting a suitable reference voltage setting point for the OLTC dynamically without communication systems.

6.2 Automatic Compensation Voltage Control technique

The voltage of 11kV distribution networks is lowest voltage level that can be controlled by using OLTC transformer with AVC relay. Since the voltage at 11kV feeders and further down-stream networks is impacted depending on load demand and DG penetration without measurement, the most affected voltage level of distribution networks caused by high DG penetration is 11kV networks therefore the distribution networks for demonstration purpose are chosen to be 11kV networks in this Section.

An AVC relay with LDC technique is used to compensate the voltage drop caused by load variety by DNOs. Conventionally when the maximum voltage drop occurs at the end of feeder under peak load demand, the secondary voltage of transformer is increased by the OLTC to restore the voltage level along the feeder. A lower voltage level is applied to OLTC during minimum load condition. However, it is difficult to employ LDC in practical distribution networks since the transformer may supply several feeders which have different load profiles results in the complicate LDC setting. Furthermore, the DG penetration will make things worse for the LDC function. LDC are therefore either not used or used with a compromise setting that results in a strict limitation on DG capacity connected to networks under the worst case scenarios used by the DNOs.

The Automatic Compensation Voltage Control (ACVC) technique is based on AVC relay with LDC function to estimate not only the voltage drop but also the voltage rise caused by DG penetration along multiple feeders according to the feeder's power flow direction and current magnitude as well as knowledge of the network topology with DG location of each feeder. As an extension of LDC function, ACVC can accommodate feeder line voltage rise as well as feeder line voltage drop. When a DG is connected to local distribution networks, the feeder current magnitudes and power flow directions are used to solve the conventional LDC error by applying a suitable reference voltage setting point for AVC relay. Therefore it is expected to allow larger capacities of DG to be connected and the voltage control performance would be improved. The conventional OLTC voltage controls with LDC take the assumption that the power flow is only in one direction and the voltage drop is shown in equation (21):

$$\Delta V_{drop} = |I_T| Z_{SET} \tag{21}$$

The R+jX line impedance model simulated in conventional LDC is always based on a theoretical composite feeder which can satisfy the demands with an assumption that the worst combined scenario of each feeder occurs at the same time. No reversed power flow is allowed with the conventional LDC. This significantly limits DG penetration level.

However, the ACVC control method takes power flow direction into consideration to cope DG integrations. The R+jX line impedance model of each feeder is simulated with its own impedance parameters to establish Z_i using load profile and network data by off-line power flow calculation without DG penetration [154]. The off-line power flow calculation method is attached as Appendix A. Therefore a simplified distribution networks where each feeder is simulated as a lumped load connected at the feeder end without DG. The estimated feeder impedance Z_i (line resistance R_{SET} and line reactance X_{SET}) can be obtained and is the Z_{SET} in LDC function defined in equations (5) and (6) when there is a small amount of DG power exported in i^{th} feeder and the current I_i will be the same direction as when there is no DG. When there is a large amount of DG power which exceeds the local load in one feeder, the power flow direction will be reversed. The improved feeder impedance Z_i' under this situation is estimated as follows:

$$Z_i' = \frac{\text{DG Distance}}{\text{Feeder Length}} \times Z_i \tag{22}$$

The Z_i' represents the estimated impedance from sending-end busbar to the DG connection busbar. When the power flow direction is reversed, voltage rise of DG connection point must be considered primarily. The ratio of distance between DG connection point and sending-end busbar over the whole feeder length is used with the estimated feeder impedance Z_i to obtain the Z_i'. If there is more than one DG on one feeder, the DG distance will use the farthest for the estimation in order to ensure the feeder voltage will not exceed the upper limits.

The compensation voltage ΔV_i of each feeder is obtained by equations (23) and (24). If DG output power of i^{th} feeder matches the feeder load, the feeder current will be zero and the compensation voltage ΔV_i of this feeder will be set as zero. When power flow is reversed, the compensation voltage is set as voltage rise by equation (24) and voltage drop as equation (23) with the small DG. The compensation voltage of the i^{th} feeder ΔV_i is as follows:

$$\Delta V_i = -V_{dropi} = -|I_i| Z_i \tag{23}$$

$$\Delta V_i = V_{risei} = |I_i| Z_i' \tag{24}$$

The advanced control algorithm using ACVC is presented to explain how to choose reference voltage setting point of OLTC with AVC relay by the ΔV_i of each feeder. One of the feeders in the 11kV distribution network is modelled in Simulink of MATLAB® to evaluate the ACVC technique as shown in Figure 65.

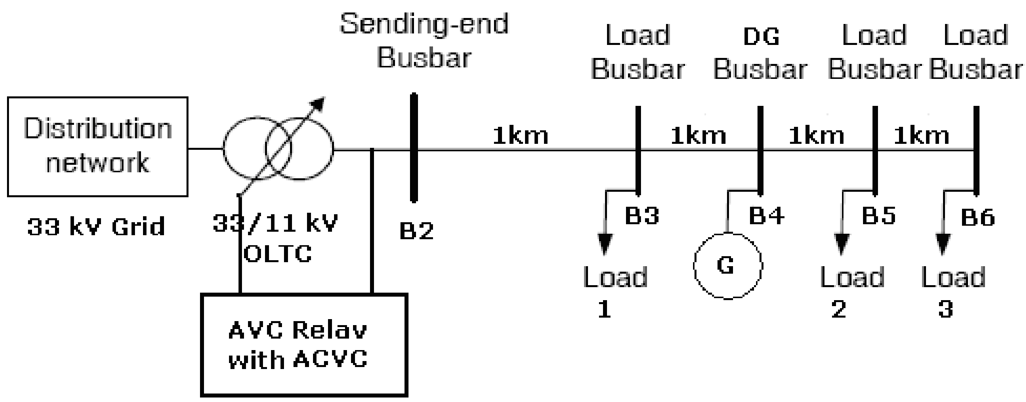


Figure 65. One feeder of a 11kV distribution network complete with DG

The ΔV is used to compensate the measured secondary voltage of OLTC transformer as equation (25) to select the reference voltage setting point of AVC.

$$V_{SET} = V_{Sending\text{-}end} + \Delta V = \begin{cases} V_{Sending\text{-}end} + |I| Z & if \quad I > 0 \\ V_{Sending\text{-}end} - |I| Z' & if \quad I < 0 \end{cases} \tag{25}$$

This network model consists of a 33kV grid source, a 33/11kV OLTC transformer with AVC relay using ACVC technique, one feeder with three loads and one DG. The short circuit level of the grid is 1000MVA.

The OLTC transformer model is rated at 100MVA with 7.5% reactance. Each tap step is 1.43% with 1 second time delay and the total tap range is ±8, which are 17 tap positions in total. The AVC relay deadband is 1% of nominal voltage value. Each line between two busbars is 1km length and consists of 70mm^2 Alpex [125] underground cable. The simplified network is modelled by off-line power flow calculation with DG on the minimum and maximum load conditions as shown in Figure 66. The parameters of the network are shown in Table 14.

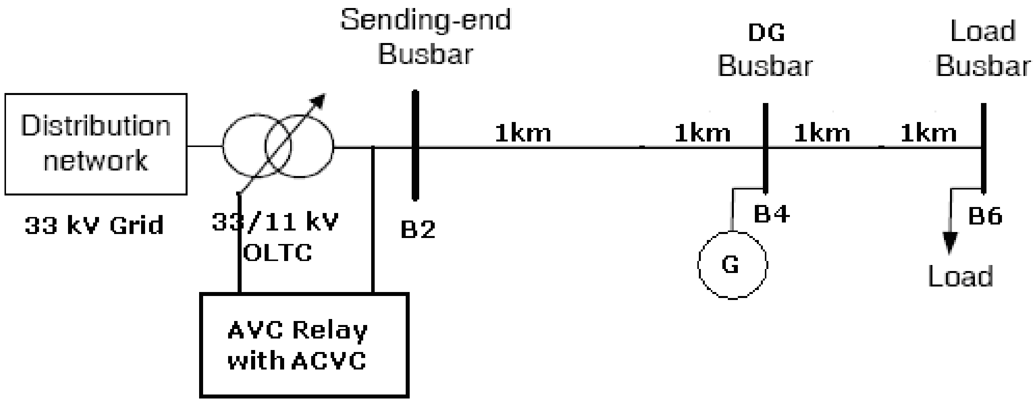


Figure 66. Simplified network

Table 14. Network parameters

Original network		Simplified network	
$V_{network}$	11kV	$V_{network}$	11kV
Resistance	0.443Ω/km	Resistance	0.277Ω/km
Reactance	0.076Ω/km	Reactance	0.048Ω/km
Load 1	1MW	Load	3MW
Load 2	1MW	DG distance	2km
Load 3	1MW	DG pf	1.0

6.2.1 Minimum load condition

The minimum load condition is 0.2 pu of full load and therefore each load is 0.2MW. The voltage profile of OLTC with AVC relay using ACVC technique along the feeder is shown in the following Figures with different levels of DG output. These are compared with the profile using the conventional AVC method with LDC.

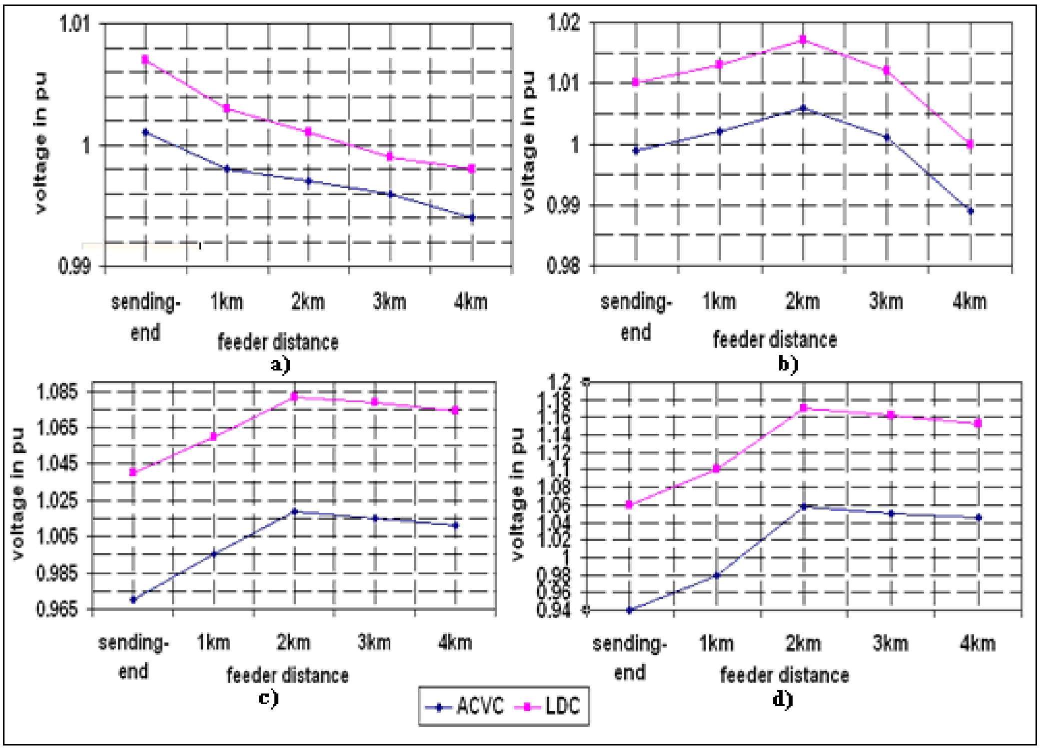


Figure 67. Voltage profile under minimum load condition

(a) DG=0, (b) DG=1MW, (c) DG=3MW, (d) DG=5MW

From Figure 67 (a), it can be seen that ACVC technique has the similar performance to the conventional method when there is no DG output. When the DG is 1MW, the DG generation exceeds the minimum load demand thus the power flow is reversed as shown in (b). The LDC (pink line) considers this voltage rise as voltage drop and increases the reference voltage setting point however ACVC (blue line) can recognize the voltage rise and decrease the secondary voltage of OLTC transformer. Since the amount of DG output is small thus the LDC can still be used. In (c) it can be observed that the 3MW of DG output is relative large compared to load demand, the LDC (pink line) further increases the voltage of sending-end busbar resulting in an overvoltage at the DG connection point. The ACVC (blue line) has the capability to solve voltage rise problem caused by DG. With 5 MW DG, LDC (pink line) makes the voltage rise problem worse and ACVC (blue line) is still operating correctly as shown in (d). The DG capacity is increased significantly from 1MW to 5MW when using ACVC technique compared to LDC function under minimum load condition.

6.2.2 Maximum load condition

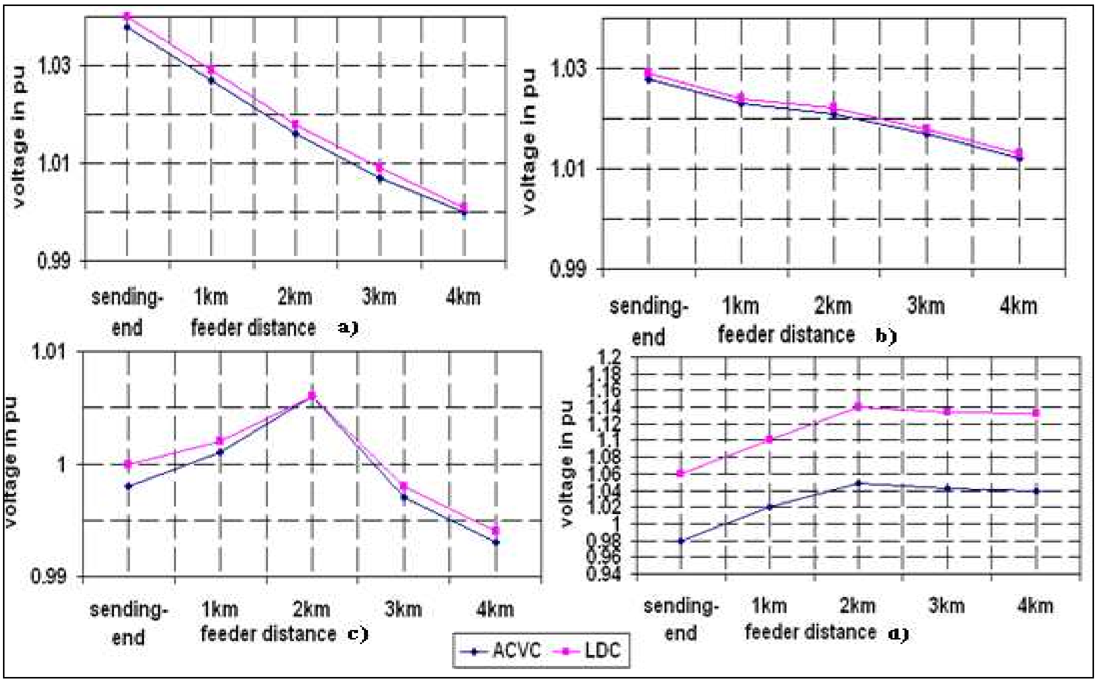


Figure 68. Voltage profile under maximum load condition

(a) DG=0, (b) DG=1MW, (c) DG=3MW, (d) DG=5MW

From Figure 68 (a) and (b), it can be seen that ACVC control based AVC relay can provide voltage control performance (blue line) similar to that using conventional AVC relay with LDC (pink line) when DG output is less than load demand. Figure (c) indicates that the current is nearly zero when DG output is close to load. Thus initial voltage setting V_{SET} is applied where LDC uses 1.0 pu and ACVC uses 0.985 pu. Figure (d) shows that OLTC with AVC relay using ACVC can reduce DG impacts on voltage. This would enable more DG output power to be exported to the feeder.

In summary, the results obtained from simulations show that ACVC technique can be used to set reference voltage setting point for an AVC relay to increase DG power output under different conditions in a one feeder network. In practical distribution networks, there are normally more than one feeder connected to the same substation and the OLTC control algorithm provides voltage control is presented as follows.

6.3 Advanced compensation-based OLTC voltage control algorithm using ACVC

In practical 11kV distribution networks, the maximum number of feeders from a 33/11kV substation is based on configuration of network and maximum utilization. The average number of feeders connected to one 33/11kV substation ranges from 3 to 8 in the UK according to the published information of Long Term Development Statement (LTDS) from DNOs [123, 155, 156]. A generic 11kV multi-feeder distribution network with DG connections has been shown in Figure 69.

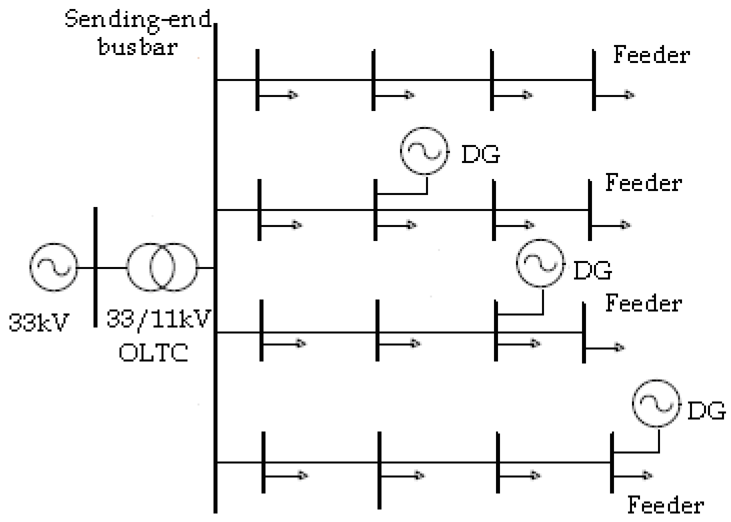


Figure 69. An 11kV multi-feeder distribution network

The load varies at different time of the day due to the behaviour of people with different amounts of power used. The composition of different customer types at each feeder results in different load profile. In OLTC voltage control using ACVC technique, the minimum and maximum load conditions of each feeder is calculated by off-line power flow study without consideration of DG. Moreover, the simulated line impedance Z_i is created and every feeder is simplified to a lumped load is connected at the feeder end via simulated line impedance. When the power flow of one feeder detected by ACVC is not reversed, the voltage control point of this feeder is assumed to be the feeder end with the Z_i. If a reversed power flow is detected in one feeder, the Z_i' is used instead of the Z_i according to equation (22) to ensure the voltage control point corresponds to the furthest DG connection point. The current of each feeder is measured by current transformer (CT) to create a compensation voltage ΔV_i by equation (23) or (24) for each feeder. The AVC relay measures the sending-end busbar voltage V_S and provides the advanced compensation-based OLTC voltage control system with all of the compensation voltages. The function of advanced compensation-based control system is to determine a new voltage setting point V_{SET} (k+1) for AVC relay to control the sending-end busbar voltage by OLTC thus keeps all the voltages within limits. The function of advanced compensation-based OLTC with AVC relay using ACVC technique is given by equation (26) as follows:

$$V_{SET}(k+1) = V_{SET}(k) - f(V_S, V_{UL}, V_{LL}, \Delta V_i, V_{DB}) \tag{26}$$

$$f(V_S, V_{UL}, V_{LL}, \Delta V_i, V_{DB}) =$$

$$\begin{cases} V_S + \dfrac{\sum_{i'=1}^{k'} \Delta V_{i'}}{k'} - V_{UL} + V_{DB} \\ if \forall (V_S + \Delta V_i - V_{UL}) > 0 \wedge \forall (V_S + \Delta V_i - V_{LL}) > 0 \wedge Max(V_S + \Delta V_i - V_{UL}) - Min(V_S + \Delta V_i - V_{LL}) > 0 \\ V_S + \dfrac{\sum_{i'=1}^{k'} \Delta V_{i'}}{k'} - V_{LL} - V_{DB} \\ if \forall (V_S + \Delta V_i - V_{UL}) < 0 \wedge \forall (V_S + \Delta V_i - V_{LL}) < 0 \wedge Max(V_S + \Delta V_i - V_{UL}) - Min(V_S + \Delta V_i - V_{LL}) < 0 \\ 0 \qquad if \forall (V_S + \Delta V_i - V_{UL}) \leq 0 \wedge \forall (V_S + \Delta V_i - V_{LL}) \geq 0 \\ Alarm \qquad if \forall (V_S + \Delta V_i - V_{UL}) > 0 \wedge \forall (V_S + \Delta V_i - V_{LL}) < 0 \end{cases}$$

where V_{SET} (k+1) is the new voltage reference setting for AVC relay, V_{SET} (k) is the current voltage reference setting point of AVC relay, feeder voltage upper limit (V_{UL}), feeder voltage lower limit (V_{LL}), each feeder compensation voltages ΔV_i and AVC relay deadband V_{DB}. In function *f*, $\Delta V_i'$ is the selected voltage compensation if overvoltage occurs on this feeder and the $V_S+\Delta V_i'-V_{UL}$ is each voltage rise over the upper limit. On the other hand, when undervoltage occurs at one feeder, the compensation voltage is selected as $\Delta V_i'$ and the $V_S+\Delta V_i'-V_{LL}$ is each voltage drop below the lower limit. If overvoltage and undervoltage occur together for the different feeders, the voltage problem cannot be solved by OLTC and an alarm signal is issued. k′ is the number of the feeder without limits. The flow chart of advanced compensation-based OLTC voltage control algorithm is described in Figure 70.

The ACVC measures the current of each feeder and employs the simulated feeder impedance according to power flow direction using equations (23) and (24) to create compensation voltage ΔV_i for each feeder respectively. The voltage drop or voltage rise is determined and the compensation voltages ΔV_i are used with the local voltage measurement V_S to the advanced compensation-based decision maker to determine a new reference voltage setting point for OLTC with AVC relay by equation (26). The new setting of $V_{SET}(k+1)$ is compared with the voltage of sending-end busbar V_S. When the difference $V_{SET}(k+1)-V_S$ is larger than the deadband of AVC relay, relevant OLTC operation occurs to tap down in order to lower the voltage of sending-end busbar. When the $V_S-V_{SET}(k+1)$ is larger than the deadband, tapping up the OLTC occurs. The $V_{SET}(k+1)$ is update to $V_{SET}(k)$ at the same time when the OLTC is operating to prepare for the next control cycle. If there are voltages over upper limit and below lower limits at the same time, it is impossible to control the feeder voltage by OLTC voltage control system. An alarm will be sent to the DNO and a pre-set voltage setting point $V_{PRE\text{-}SET}$ 1.03 pu is used to reset when the control algorithm is failure. When the voltages are all within the certain limits, no tap action will be operated to reduce the total number of tap operation.

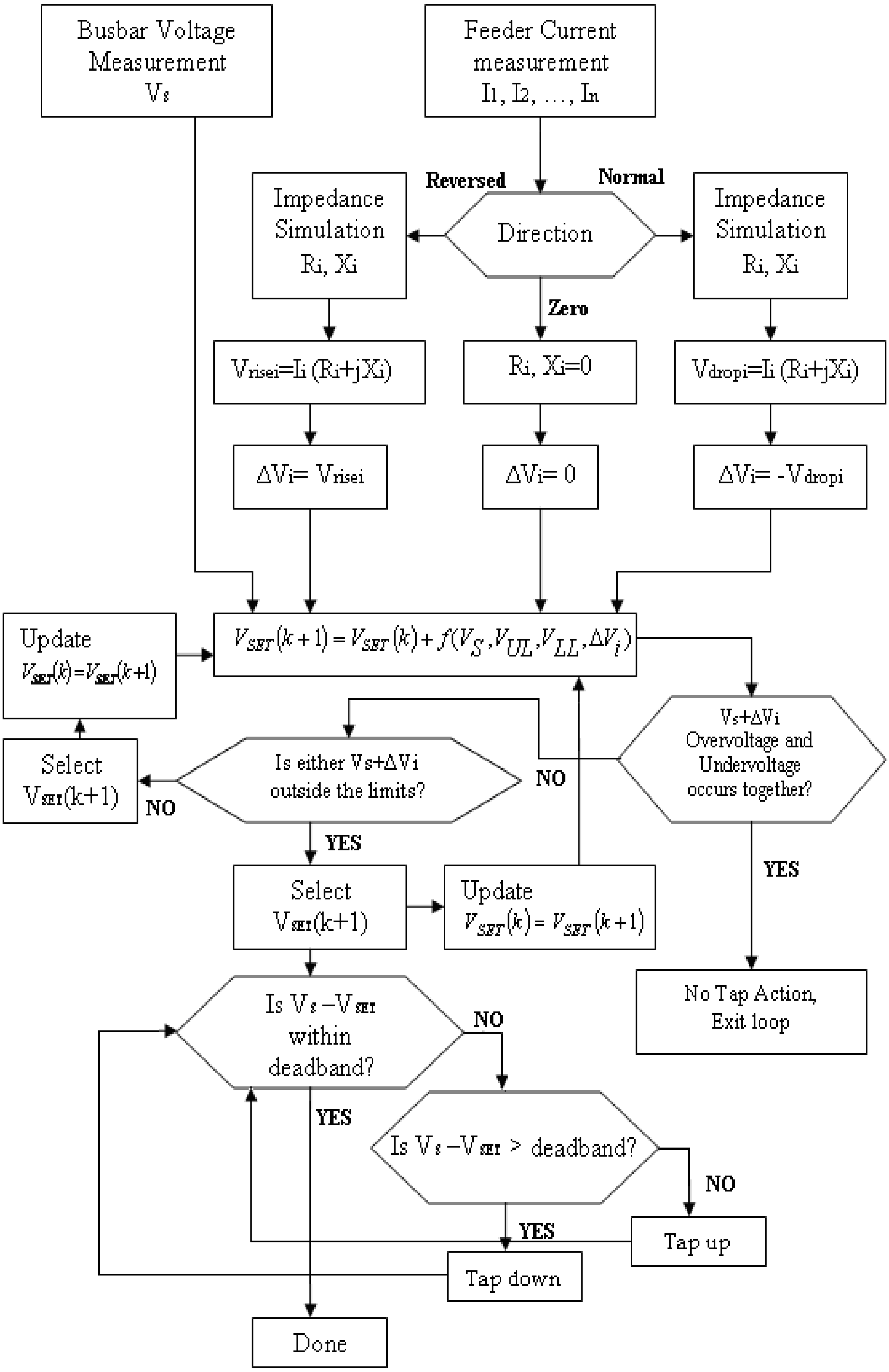


Figure 70. Flow chart of compensation-based control algorithm

The separate line impedance of each feeder model used in ACVC technique has a better performance than single composite impedance model used in conventional OLTC voltage control. Different feeders which have different load profiles are supported by this new control algorithm. The benefit of advanced compensation-based OLTC voltage control algorithm is that it can be used under different conditions by using simple relations of power flow direction and reference voltage setting point. This method reduces the design development cycle, simplifies design complexity and improves control performance. Different configurations of network can adopt using this algorithm without significant changes by adjusting the parameters of networks. The very simple arrangement is very robust without impacts by various power factor or reversed power flow. The simulations in Section 7.1 demonstrate the control performance of advanced compensation-based OLTC voltage control with an AVC relay using ACVC technique.

The constraining factor of this advanced control algorithm is the available range of tap position on OLTC transformer. With a high level of DG penetration in some particular cases, the tap changer may reach the lowest position thus losing OLTC voltage control. This OLTC transformer runaway problem cannot be solved by voltage control methods since it is caused by the limitation of OLTC transformer itself. Fortunately, the range of most OLTC transformers is adequate under most conditions and only extremely high level of DG penetration under emergent scenarios may cause the runaway problem. Another limitation is this method can only be used in radial distribution network not meshed networks.

Chapter 7

Simulation case studies of sensitive analysis

The advanced compensation-based OLTC voltage control algorithm using ACVC is simulated under different network conditions by a series of test models. Then the proposed voltage control algorithm is modelled in a UK generic distribution network in order to demonstrate the performance. A comparison study is also provided with the most recent developed methods by other researchers.

7.1 Case studies of proposed advanced compensation-based OLTC voltage control algorithm under different system conditions

The voltage rise problem usually occurs during light load and large output from the DG generation condition and thus critically impacts the DG capacity that can be connected to networks. It is also important to bear in mind that the undervoltage may occurs when DG output is reduced significantly under a large DG generation and maximum load condition. The advanced compensation-based OLTC voltage control algorithm is simulated under these extreme network conditions to demonstrate the voltage control performance with DG penetration.

7.1.1 One-feeder network using underground cable or overhead line

The multi-feeder network as shown in Figure 69 has been used. The feeder chosen for detailed analysis is the one feeder 11kV distribution urban network using underground cables shown in Figure 71 which is modelled using Simulink of MATLAB® to evaluate the advance compensation-based OLTC voltage control algorithm using ACVC technique.

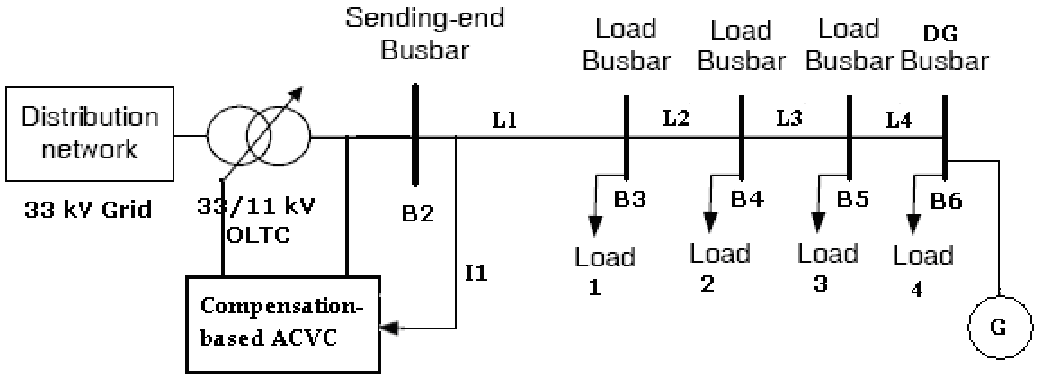


Figure 71. One feeder 11kV network with DG at the feeder end

This network model consists of a 33kV grid, a 33/11kV OLTC transformer, AVC relay with advanced compensation-based algorithm using ACVC, a feeder with four loads and one 10MW DG operating at constant unity power factor. The grid has a short circuit level of 1000MVA. The OLTC transformer model is rated at 40MVA with 7.5% reactance. The AVC relay deadband was 1%. Voltage change per tap is 1.43% with 1 second time delay. The initial reference voltage setting point is 1.03 pu. The Simulink model is shown as Figure 72. The sending-end voltage and feeder current are measured locally at the substation level and the signals are provided to the AVC relay with ACVC as input signals. The line impedance and improved impedance parameters are simulated off-line which are used as constants in the ACVC function model. The ACVC technique function model is attached in Appendix B.

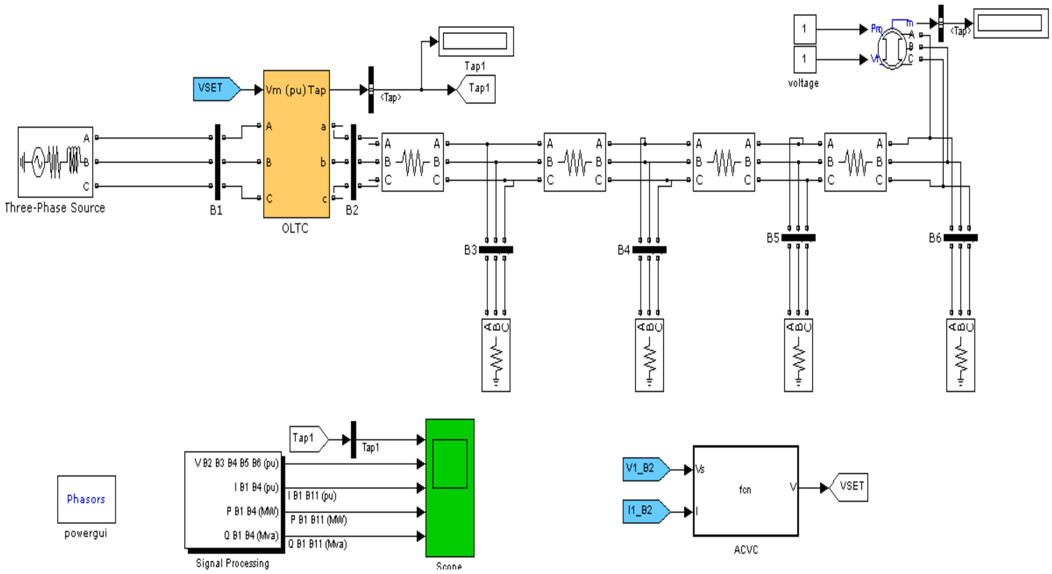


Figure 72. Simulink model of test network

Most of load in urban distribution network is normally within 2 km distance from substation. Line length and loads are listed in Table 15. The resistance and reactance of each line section is obtained from practical network data. The 95mm² AI Triplex [125] underground cable data of 0.320+j0.119Ω/km is chosen due to the dimension of this cable is used in many new networks to accommodate the growing DG capacity [126].

Table 15. Network data

$V_{network}$	11kV
L_1 length	0.2km
L_2 length	0.5km
L_3 length	1.0km
L_4 length	1.5km
Load 1, Load 4	1MW
Load 2, Load 3	2MW

In order to demonstrate the worst case scenarios, the minimum load condition is chosen as 0.1 pu of total load demand for each load and the maximum load condition is 1.0 pu. From the above simulation results in Section 6.2, the voltage rise occurs when DG output is much larger than load demand thus the maximum DG generation is considered in this case. The voltage profile of ACVC scheme is compared with conventional AVC relay without LDC due to the DG connection in Figure 73. When DG output is 10MW under maximum load condition, the voltage of DG connection point is over the upper limit with V_{SET} of 1.03 pu voltage setting for the conventional OLTC voltage control as the blue line in Figure 73 (a). Because of reversed power flow, voltage rise is simulated as the voltage compensation and the new reference voltage setting point V_{SET} is calculated by the advanced compensation-based decision maker as 1.009 pu. The tap down action is operated. When the voltage of sending-end busbar V_S is 1.001 pu, the DG connecting point voltage is 1.047 pu and within the limits by only two tap down operations as the pink line in Figure 73 (a). When 10MW DG is exported under the minimum load condition, new reference voltage setting point V_{SET} is 0.964 pu and tap down action is operated until the voltage of sending-end busbar V_S reduced to 0.958 pu. The voltage of DG connection point is reduced from 1.123 pu which is out of upper limit under conventional OLTC voltage control as blue line to 1.053 pu by 5 tap down operations under ACVC scheme as the pink line in Figure 73 (b).

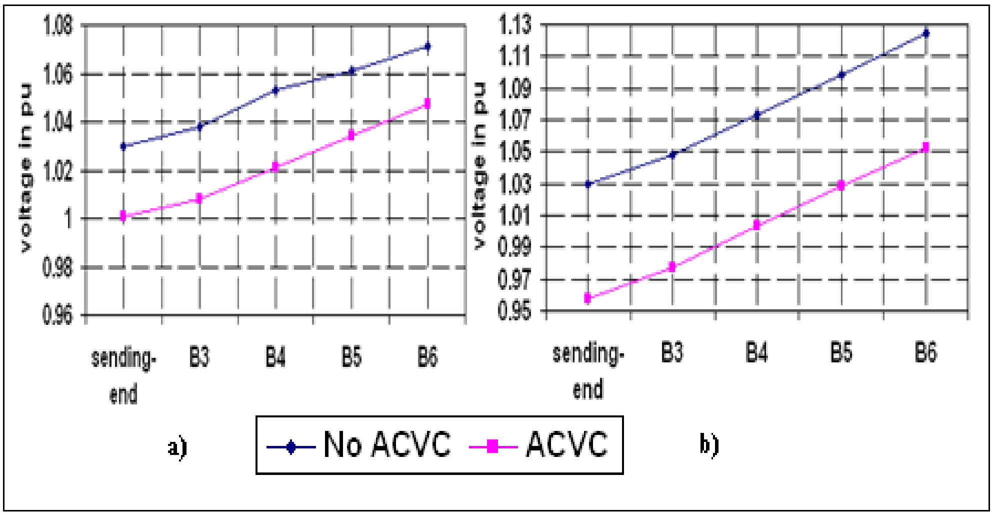


Figure 73. OLTC voltage control performance

(a) maximum load, (b) minimum load conditions

When the 100mm^2 AAAC Oak [125] overhead line data of 0.277+j0.351Ω/km is chosen due to the dimension of this line is used in many existing and new built networks [126]. The voltage profile shown in Figure 74 is nearly the same as using underground cable.

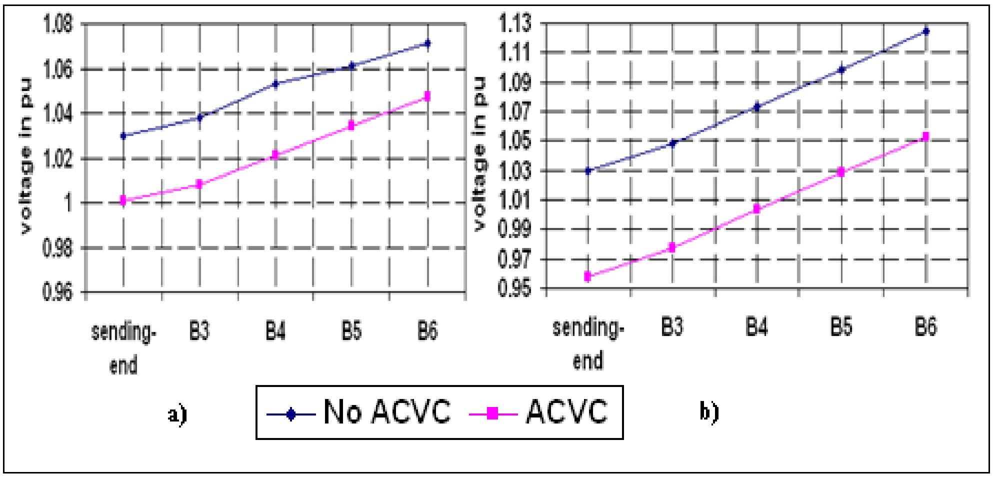


Figure 74. OLTC voltage control performance
(a) maximum load, (b) minimum load conditions

In summary, the results obtained from the one feeder network simulation show that advanced compensation-based OLTC voltage control using ACVC technique can be used to set reference voltage setting point automatically for an AVC relay to accommodate DG penetration.

7.1.2 Two-feeder network under different DG and load conditions

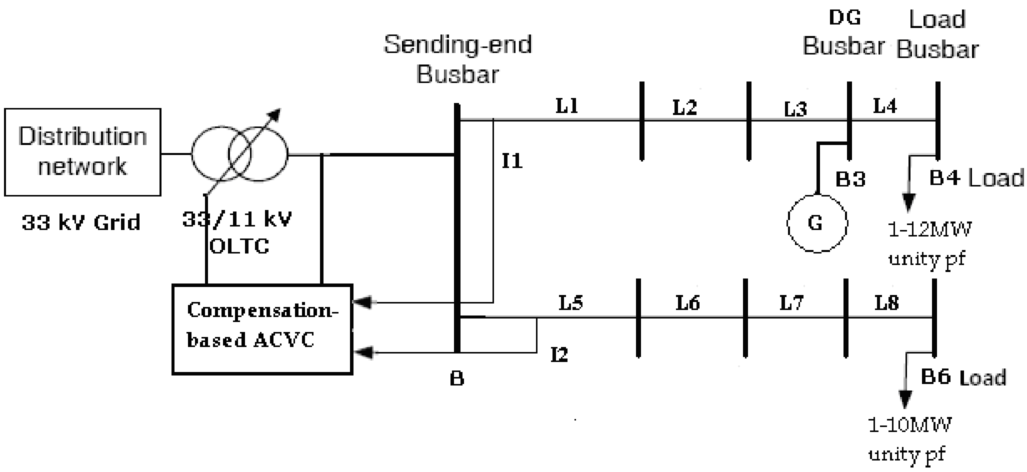


Figure 75. Two-feeder network with compensation-based algorithm

This network model consists of a 33kV grid, a 33/11kV OLTC transformer, AVC relay with advanced compensation-based ACVC, and first feeder with one DG operating at constant unity power factor together with a load at the end of the feeder. The second feeder has a load connected at the remote end of the feeder as shown in Figure 75. The grid has a short circuit level of 1000MVA. The OLTC transformer model is rated at 100MVA with 7.5% reactance. The AVC relay deadband was 1%. Voltage change per tap is 1.43% with 1 second time delay. Line impedances are as used in Study 1 given in Table 15 and load parameters are listed in Table 16. The Simulink model is shown as Figure 76.

Table 16. Network data

$V_{network}$	11kV
L_1 L_5 length	0.2km
L_2 L_6 length	0.5km
L_3 L_7 length	1.0km
L_4 L_8 length	1.5km
Load at B_4	1-12MW
Load at B_6	1-10MW

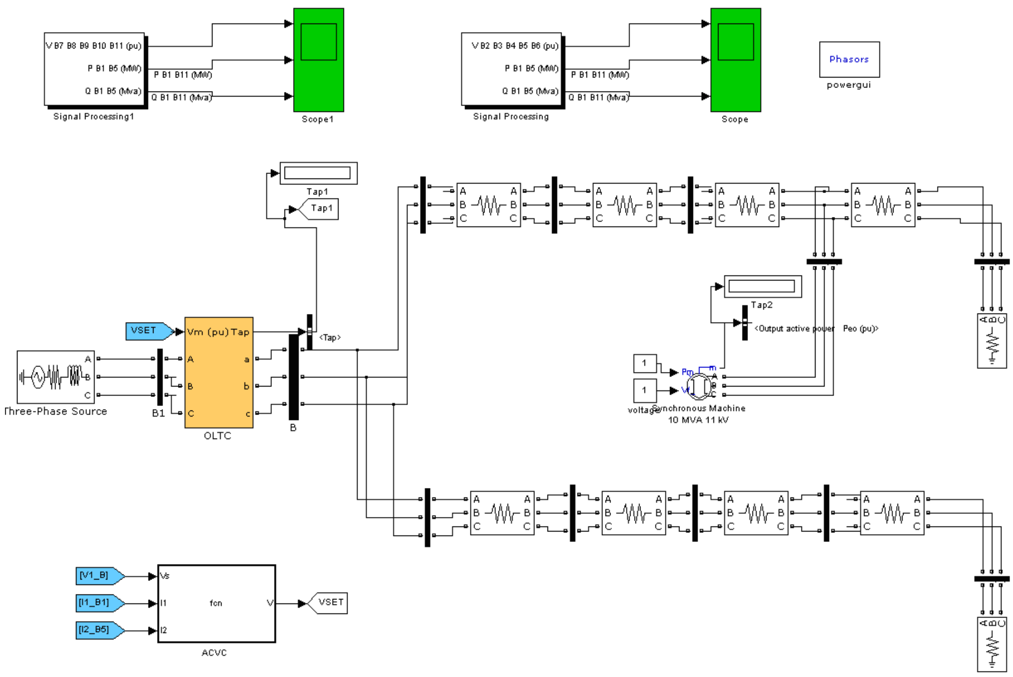


Figure 76. Simulink model of two-feeder network

7.1.2.1 Maximum load condition

The maximum value of the variable load is considered in this case, where the load at bus B_6 is 10MW and load at B_4 is 1MW. Initially V_{SET} of AVC relay is set at 1.04 pu and the DG output power is 10MW with unity power factor. The feeder voltages without ACVC and with advanced compensation-based ACVC are shown in Figure 77.

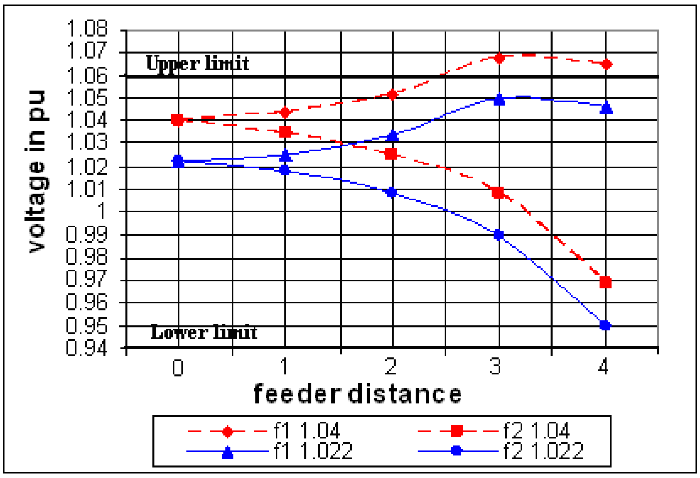


Figure 77. Voltage profiles under maximum load condition

From Figure 77, it can be seen that the sending-end busbar voltage V_S is maintained at 1.04 pu without advanced compensation-based OLTC voltage control algorithm however the voltage of DG connection point B_4 is 1.068 pu, which exceeds the upper limit 1.06 pu. Without any control algorithm, this overvoltage cannot be solved since the sending-end busbar voltage V_S is within the deadband and the AVC relay will not issue any tap changing action signal to OLTC transformer. When advanced compensation-based ACVC algorithm is used, the voltage rise of feeder 1 and voltage drop of feeder 2 is simulated and then provided to compensation-based decision maker as the voltage compensations. Therefore the overvoltage of feeder 1 is detected. The new reference voltage setting point V_{SET} is calculated as 1.022 pu then the V_{SET} for AVC relay is changed from 1.04 pu to 1.022 pu. The tap down action is operated by OLTC immediately. When the voltage of sending-end busbar

V_S is 1.024 pu which is within the AVC relay deadband, the voltage of DG connection point V_{DG} is changed from 1.068 pu to 1.05 pu which is within the limits. No overvoltage or undervoltage is detected therefore the control loop is completed.

7.1.2.2 DG power reduced under maximum load condition

In the previous case Section 6.4.2.1, the sending-end busbar voltage V_S is changed to 1.024 pu to keep the voltages along feeders within the statutory limits under maximum load condition. In this case, the variable load at B_6 is still 10MW but the DG output is reduced to 1MW and the load at busbar B_4 is increased to maximum value 12MW.

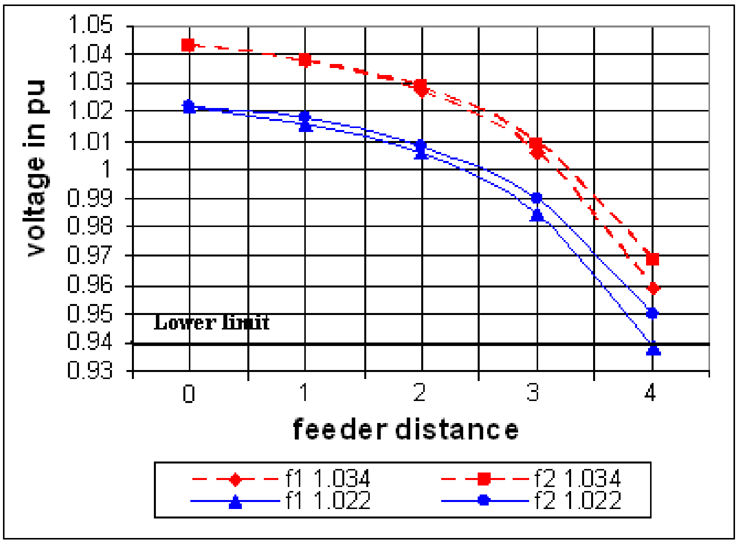


Figure 78. Voltage profiles under maximum load and reduced DG output

From Figure 78, it can be seen that the initial V_{SET} is 1.022 pu and sending-end busbar voltage V_S is 1.021 pu. Since the DG power output is reduced from 10MW to 1MW and the load of B_4 is 12MW, power flow of feeder 1 is from the grid to the feeder end, therefore the voltage rise no longer exists and instead the voltage compensation for feeder 1 is voltage drop across feeder 1. The voltage drop of feeder 1 causes undervoltage at load busbar B_4 is 0.063 pu, which is under 0.94 pu lower limit. The ACVC detects the undervoltage and a new reference voltage setting point V_{SET} for AVC relay is calculated by the compensation-based decision maker as 1.034 pu. V_{SET} is 1.034 pu and AVC relay compares measured sending-end busbar voltage V_S 1.021 pu with V_{SET} and a tap up operation command is send to the OLTC. When V_S is 1.043 pu which is within the deadband of AVC relay, the voltage of B_4 and B_6 is 0.959 pu and 0.969 pu respectively. Without any further overvoltage or undervoltage, the voltage control operation is completed.

7.1.2.3 Light load condition

This is the case that light load condition is considered with increased DG output power as shown in Figure 79 and Figure 80. Initially V_{SET} is 1.04 pu and V_S, the measured voltage of sending-end busbar is 1.036 pu and the two loads of B_4 and B_6 are both 1 MW. The DG output power is 10MW with unity power factor first in Figure 79.

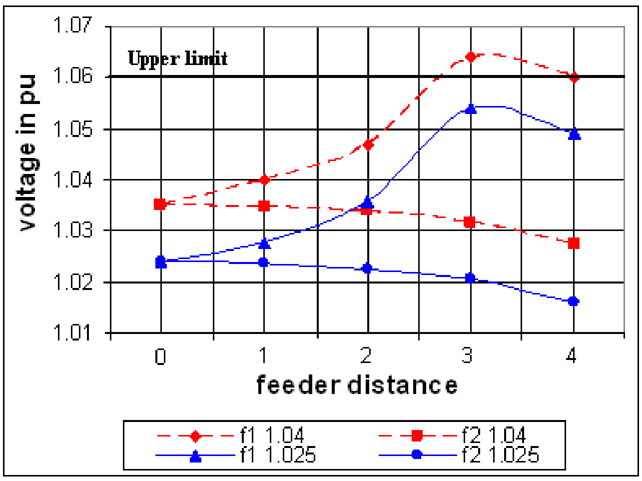


Figure 79. Voltage profiles under light load with 10MW DG

It can be seen from Figure 79 that the voltage of DG connection point is 1.065 pu which is over the upper limit initially. The ACVC detects voltage rise by reverse power flow and simulated voltage rise is used for compensation. A new reference voltage setting point is obtained by the compensation-based decision maker as 1.025 pu. V_{SET} of 1.025 pu is used to regulate the voltage of the system. When measured voltage of sending-end busbar V_S is 1.023 pu which is with the AVC relay deadband, the voltage of B_3 is 1.054 pu, where the voltage of DG connection point is within the upper limit.

When the DG output power is increased from 10MW to 20MW, the voltage profile is shown as Figure 80.

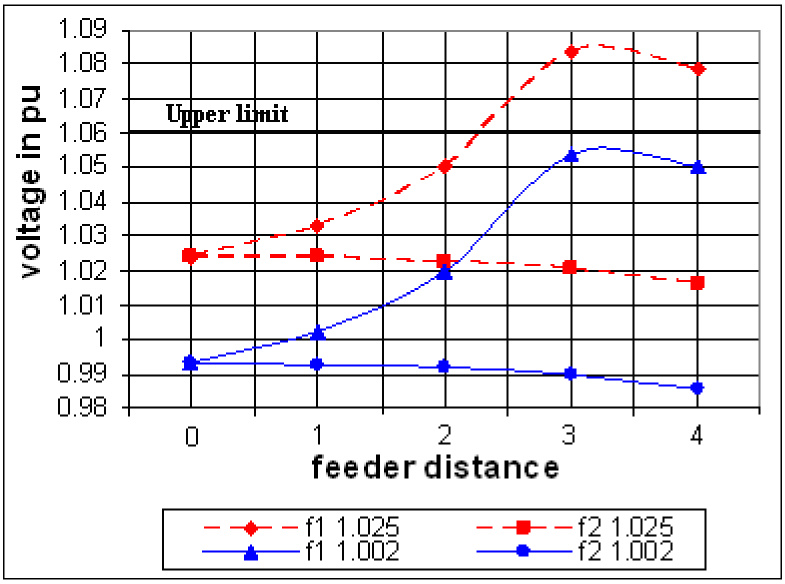


Figure 80. Voltage profiles under light load with 20MW DG

From Figure 80, when DG output power is increased from 10MW to 20MW and V_{SET} is 1.025 pu, the voltage of DG connection point at B_3 is 1.084 pu which is over the upper limit. The voltage rise is detected and a new voltage setting point V_{SET} of 1.002 pu is provided to AVC relay. V_{SET}

as 1.002 pu instruct OLTC to change tap position. The voltage of sending-end busbar V_S is changed from 1.023 pu to 0.994 pu and V_{DG} from 1.084 pu to 1.054 pu, which is within the set limits.

The capacity of DG power output that can be connected to a distribution feeder without causing overvoltage has therefore increased by using the advanced compensation-based OLTC control algorithm. It also provides a function similar to LDC when there is a significant voltage drop along the feeder.

7.1.3 13-bus distribution network under different DG and load conditions

The 11kV 13-bus distribution network is simulated using Simulink MATLAB® representing a typical UK regional distribution network in Figure 81.

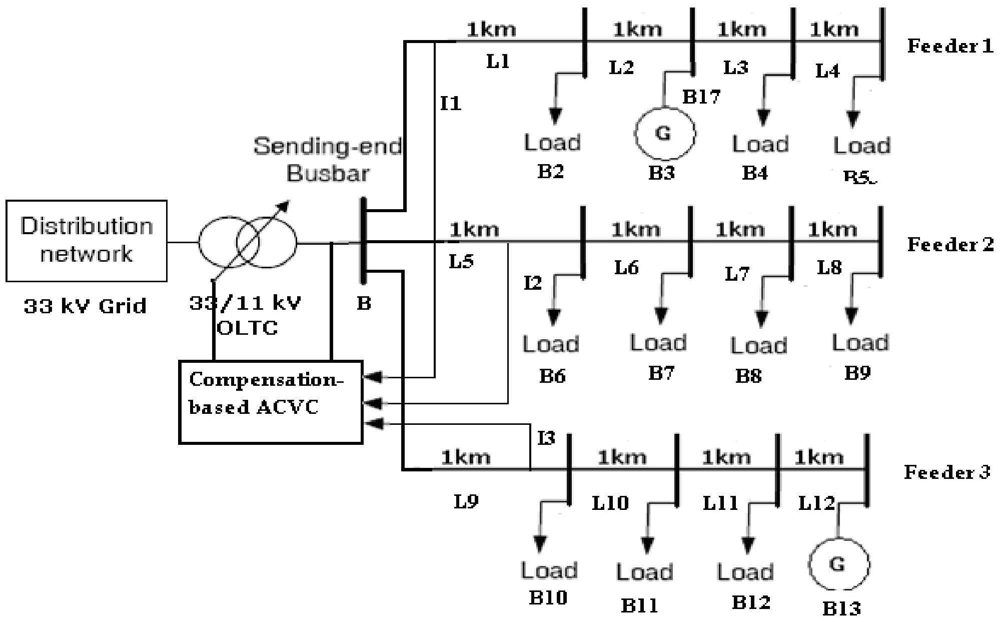


Figure 81. Radial distribution network using compensation-based ACVC

This network model consists of a 33kV grid, a 33/11kV OLTC transformer, AVC relay with compensation-based ACVC technique, three feeders, ten load centres and two distributed synchronous generators operating with unity power factor. The first feeder has one DG at the bus B_2, 2km from the sending-end busbar. The second feeder is a pure load feeder which includes one variable load from 1MW to 10MW. The third feeder has a DG at the end of feeder B_{13}. The grid has a short circuit level of 1000MVA. The OLTC transformer model is rated at 100MVA with 7.5% reactance. The AVC relay deadband was 1%. Voltage change per tap step is 1.43% with 1 second time delay. The 95mm^2 AI Triplex [125] underground cable is chosen and the line impedance data is 0.320+j0.119Ω/km. All line sections are 1km in this case with the network parameters as shown in Table 17. The model is given in Figure 82.

Table 17. Three feeder network data

$V_{network}$	11kV
Load at B_2-B_{12}	1MW
Load at B_9	1-10MW
DG at B_3	0-5MW
DG at B_{13}	0-10MW

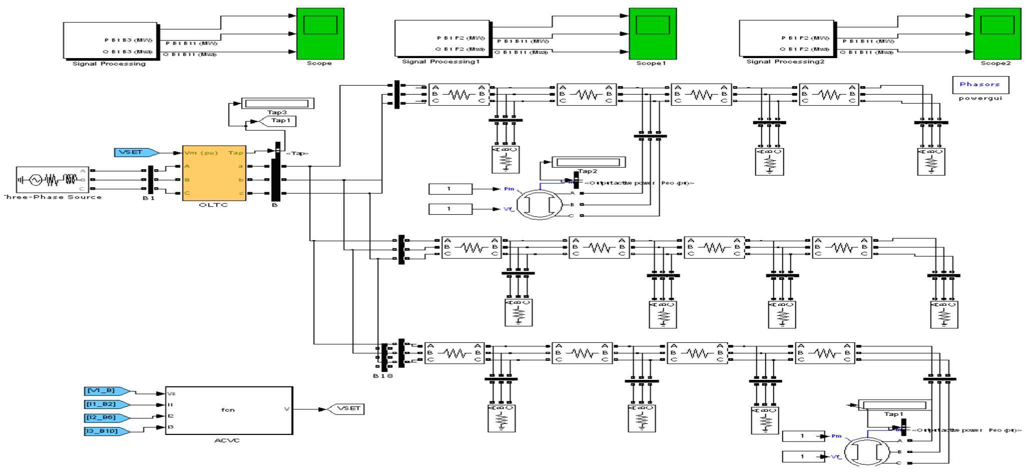


Figure 82. Simulink model of three-feeder network

7.1.3.1 Large DG output power under light load condition

In this case the maximum DG output power and light load condition are considered. The variable load at B_9 of load feeder 2 is 1MW. The DG at B_3 and DG at B_{13} are set to their maximum power output which are 5MW and 10MW respectively. The voltage of each bus is shown as Figure 83.

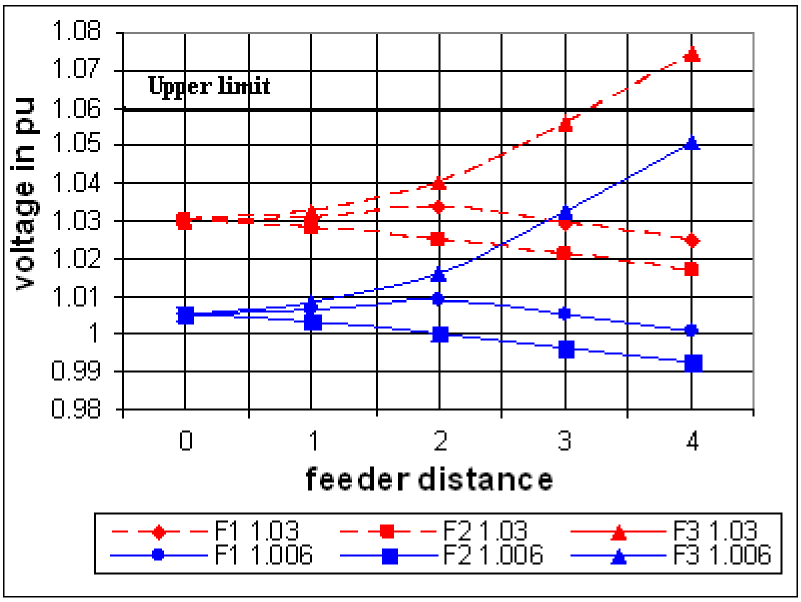


Figure 83. Voltage profiles under maximum DG and light load

From Figure 83, the reference voltage setting point of AVC relay V_{SET} is initially set at 1.03 pu to maintain the voltage of feeder end to be around 1.0 pu. However, DG at the end of feeder 3 causes the voltage at the connection point to rise to 1.0744 pu, which is over the upper limit. Since the DG at B_3 of feeder 1 is closer to the sending-end busbar than DG at B_{13}, its impact is less significant than that of the DG at the end of feeder 3. This overvoltage is detected by the ACVC and the voltage rise is simulated for new reference voltage setting point. A new voltage V_{SET} is set to 1.006 pu and AVC relay issues tap down command to the OLTC. When the measured voltage of sending-end busbar V_S is then changed from 1.03 pu to 1.0054 pu which is within the AVC deadband, V_{DG} at bus B_{13} is decreased from 1.0744 pu to 1.0512 pu. As V_{DG} is below the limit, this system has more capacity to allow more DG power exportation.

7.1.3.2 Minimum DG under maximum load condition

In this case, two DGs output is reduced to a minimum value of 1MW each and the variable load of bus B_9 is increased from 1MW to 10MW. The voltage profiles of each feeder in responding to the change of DG and load are shown in Figure 84.

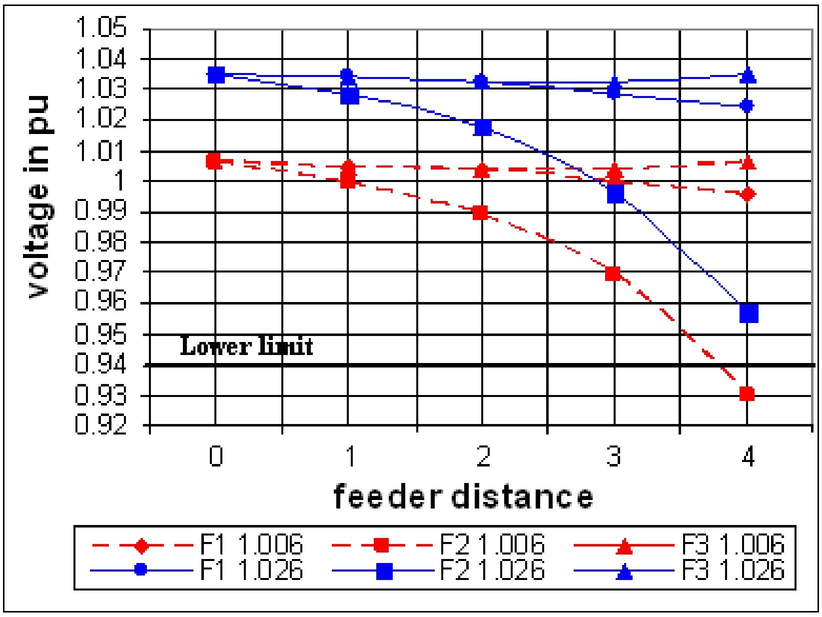


Figure 84. Voltage profiles under maximum load and light DG

From the previous case in Section 7.4.3.1, the initial V_{SET} is 1.006 pu and V_S is 1.0054 pu. When the DG reduced their output power to 1MW each and the load of B_9 is increased to 10MW, the voltage of load centre at B_9 is reduced to 0.93 pu which is lower than the limit. ACVC detects the voltage drop and provide a function similar to LDC function. A new reference voltage setting point for AVC relay is provided as 1.026 and V_{SET} 1.026 pu is used to instruct OLTC to operate tap up action in order to compensate for the voltage drop. The voltage of B_9 is changed from 0.93 pu to 0.957 pu when the measured voltage of sending-end busbar V_S is 1.0352 pu which is within the AVC deadband of 1.026 pu V_{SET}. The compensation-based ACVC method can accommodate the voltage drop problem for networks under peak load condition with suddenly reduced DG output. The voltage of sending-end can be increased according to this situation.

7.1.3.3 Large DG under large load condition

In this case the two DGs export the maximum output power while the loads are still at their maximum condition. The initial reference voltage setting point of AVC relay V_{SET} is 1.04 pu that the measured voltage of sending-end busbar V_S is 1.0347 pu. The voltage profile is given in Figure 85.

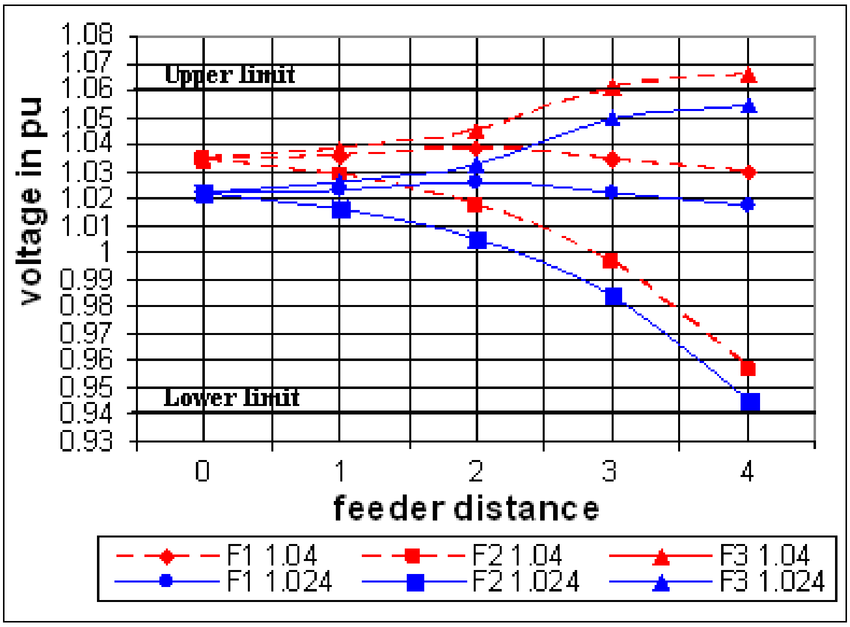


Figure 85. Voltage profile maximum DG and maximum load

The simulation results of Figure 85 shows that the overvoltage at the DG connection point B_{13} has occurred when the DG exports large amount of power under maximum load. The initial 1.035 pu value of V_S is set to compensate the voltage drop during the full load condition and this results in the DG connection point voltage being over the upper limit. This overvoltage is detected by the ACVC and a new reference voltage setting point for the AVC relay V_{SET} is set as 1.024 pu. When the sending-end busbar voltage V_S is changed from 1.035 pu to 1.02 pu by the OLTC tap down operation, the V_S is within the AVC relay deadband of V_{SET} at

1.024 pu. The voltage of DG connection point V_{DG} is changed from 1.066 pu to 1.054 pu while voltage levels along feeder 1 and at bus B_9 are kept above lower limit. The available V_{SET} range under this condition is limited since the large load at the end of the pure load feeder 2 may cause undervoltage if the V_{SET} is further reduced.

7.2 Simulation of a generic 11kV distribution network in the UK

The previous simulations have been done on test models which are simpler than practical distribution networks. A generic 11kV distribution network model (GDS) [157] given in Figure 86 was chosen in order to demonstrate the performance of advanced compensation-based OLTC voltage control algorithm using ACVC technique. The reason why this network was chosen is that it is representative of a typical 11kV distribution network format in the UK and the simulation includes the practical characteristics of such a network so as to obtain more convincing and reliable results to show the robustness of the proposed OLTC voltage control algorithm. This network includes urban, suburban and rural feeders with different load and DG levels which using different distribution lines.

The network consists of a 33kV power supply and two OLTC transformers rated at 100MVA, used for security. Eight feeders are connected to the sending-end busbar. There are 4 urban feeders (1101-1103, 1104-1106, 1107-1109 and 1110-1114) using typical underground cables, 3 suburban feeders (1115-1125, 1126-1136 and 1137-1150) using mixture lines and 1 rural feeder (1151-1175) using typical overhead lines.

There are twelve DGs in total and seventy five loads with line impedance which are listed in Table 18-20. Minimum load condition means a total power of 0.1 pu with 0.98 power factor and the maximum load condition means a total power of 1 pu with power factor 0.98 at each load point. All of DGs were operated at unity power factor. The distances were measured as the distribution line length from load busbar to substation. The network parameters were obtained from UKGDS group for practical distribution network demonstration [158].

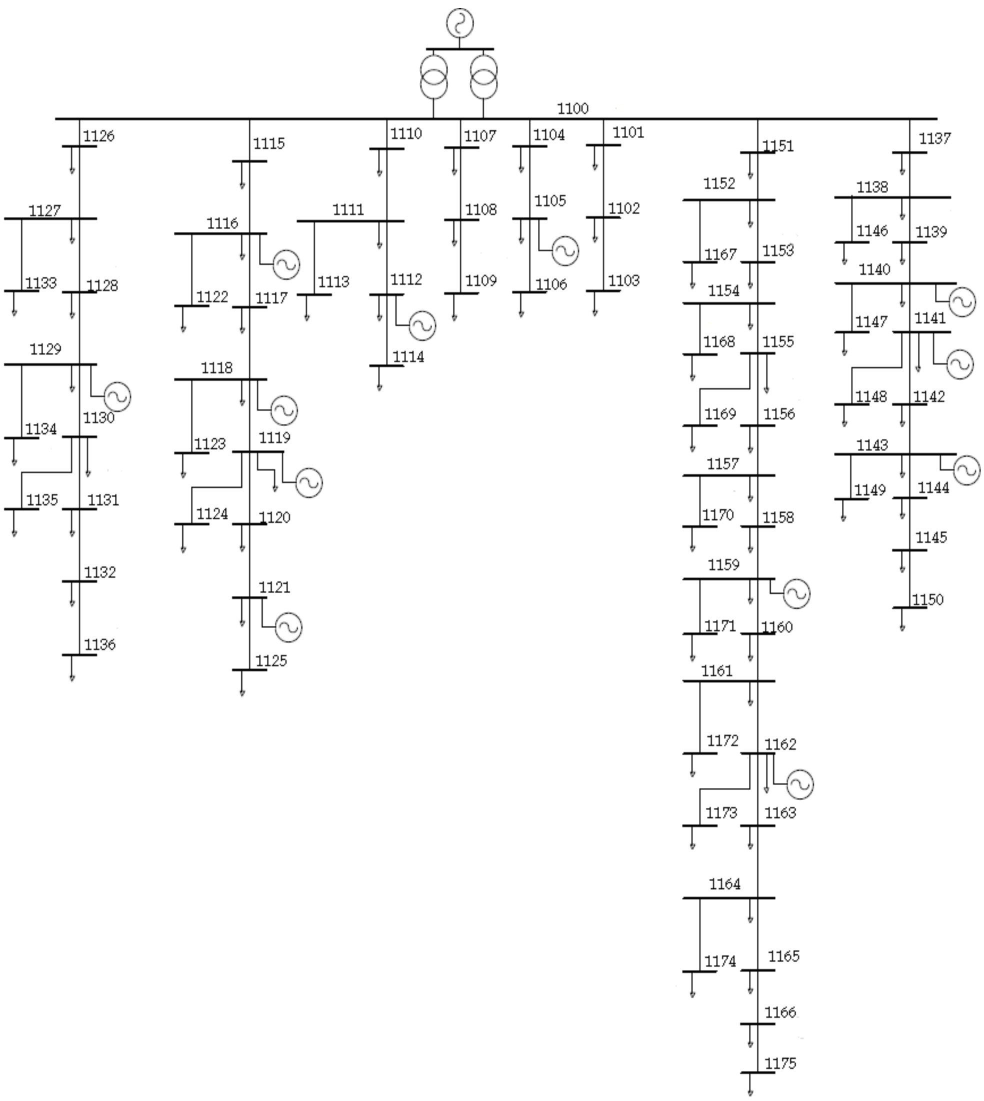


Figure 86. 75-bus generic 11kV distribution network in the UK

Table 18. Line impedance parameters (Ω)

From	To	R	X	From	To	R	X
1100	1101	0.2038	0.1056	1138	1139	0.0917	0.0706
1101	1102	0.2038	0.1056	1139	1140	0.0917	0.0706
1102	1103	0.0624	0.017	1140	1141	0.0917	0.0706
1100	1104	0.2038	0.1056	1141	1142	0.0917	0.0706
1104	1105	0.2038	0.1056	1142	1143	0.0917	0.0706
1105	1106	0.0624	0.017	1143	1144	0.0917	0.0706
1100	1107	0.2038	0.1056	1144	1145	0.0917	0.0706
1107	1108	0.2038	0.1056	1138	1146	0.0571	0.0155
1108	1109	0.0624	0.017	1140	1147	0.0571	0.0155
1100	1110	0.266	0.1378	1141	1148	0.0571	0.0155
1110	1111	0.266	0.1378	1143	1149	0.0571	0.0155
1111	1112	0.266	0.1378	1145	1150	0.0571	0.0155
1111	1113	0.0663	0.018	1100	1151	0.0665	0.0512
1112	1114	0.0663	0.018	1151	1152	0.0665	0.0512
1100	1115	0.0745	0.0574	1152	1153	0.0665	0.0512
1115	1116	0.0745	0.0574	1153	1154	0.0665	0.0512
1116	1117	0.0745	0.0574	1154	1155	0.0665	0.0512
1117	1118	0.0745	0.0574	1155	1156	0.0665	0.0512
1118	1119	0.0745	0.0574	1156	1157	0.0665	0.0512
1119	1120	0.0745	0.0574	1157	1158	0.0665	0.0512
1120	1121	0.0745	0.0574	1158	1159	0.0665	0.0512
1116	1122	0.0542	0.0147	1159	1160	0.0665	0.0512
1118	1123	0.0542	0.0147	1160	1161	0.0665	0.0512
1119	1124	0.0542	0.0147	1161	1162	0.0665	0.0512
1121	1125	0.0542	0.0147	1162	1163	0.0665	0.0512
1100	1126	0.0745	0.0574	1163	1164	0.0665	0.0512
1126	1127	0.0745	0.0574	1164	1165	0.0665	0.0512
1127	1128	0.0745	0.0574	1165	1166	0.0665	0.0512
1128	1129	0.0745	0.0574	1152	1167	0.0729	0.0198
1129	1130	0.0745	0.0574	1154	1168	0.0729	0.0198
1130	1131	0.0745	0.0574	1155	1169	0.0729	0.0198
1131	1132	0.0745	0.0574	1157	1170	0.0729	0.0198
1127	1133	0.0542	0.0147	1159	1171	0.0729	0.0198
1129	1134	0.0542	0.0147	1161	1172	0.0729	0.0198
1130	1135	0.0542	0.0147	1162	1173	0.0729	0.0198
1132	1136	0.0542	0.0147	1164	1174	0.0729	0.0198
1100	1137	0.0917	0.0706	1166	1175	0.0729	0.0198
1137	1138	0.0917	0.0706				

Table 19. Load data (MW)

bus	data	bus	data
1101	0.392	1139	0.436
1102	0.392	1140	0.436
1103	0.116	1141	0.436
1104	0.392	1142	0.436
1105	0.392	1143	0.436
1106	0.116	1144	0.436
1107	0.392	1145	0.436
1108	0.392	1146	0.216
1109	0.116	1147	0.218
1110	0.394	1148	0.218
1111	0.394	1149	0.218
1112	0.396	1150	0.218
1113	0.1	1151	0.342
1114	0.102	1152	0.342
1115	0.426	1153	0.344
1116	0.426	1154	0.344
1117	0.426	1155	0.344
1118	0.426	1156	0.344
1119	0.426	1157	0.344
1120	0.426	1158	0.344
1121	0.426	1159	0.344
1122	0.212	1160	0.344
1123	0.212	1161	0.344
1124	0.214	1162	0.344
1125	0.214	1163	0.344
1126	0.426	1164	0.344
1127	0.426	1165	0.344
1128	0.426	1166	0.344
1129	0.426	1167	0.222
1130	0.426	1168	0.222
1131	0.426	1169	0.224
1132	0.426	1170	0.224
1133	0.212	1171	0.224
1134	0.212	1172	0.224
1135	0.214	1173	0.224
1136	0.214	1174	0.224
1137	0.434	1175	0.224
1138	0.434		

Table 20. DG data

Generator Bus	P (MW)
1105	1.73
1112	1.73
1116	1.73
1118	1.73
1119	1.73
1121	1.73
1129	1.73
1140	1.73
1141	1.73
1143	1.73
1159	1.73
1162	1.73

Each DG output is 1.73 MW and the initial reference voltage setting point V_{SET} of AVC relay is 1.03 pu. The deadband of AVC relay is set to 2% in the conventional OLTC voltage control. The voltage profile of each feeder under minimum load condition using conventional OLTC voltage control is simulated in this case and the results are shown in Figure 87. Since DG output is not significantly large compared with load, only two feeders with a small amount of load are affected.

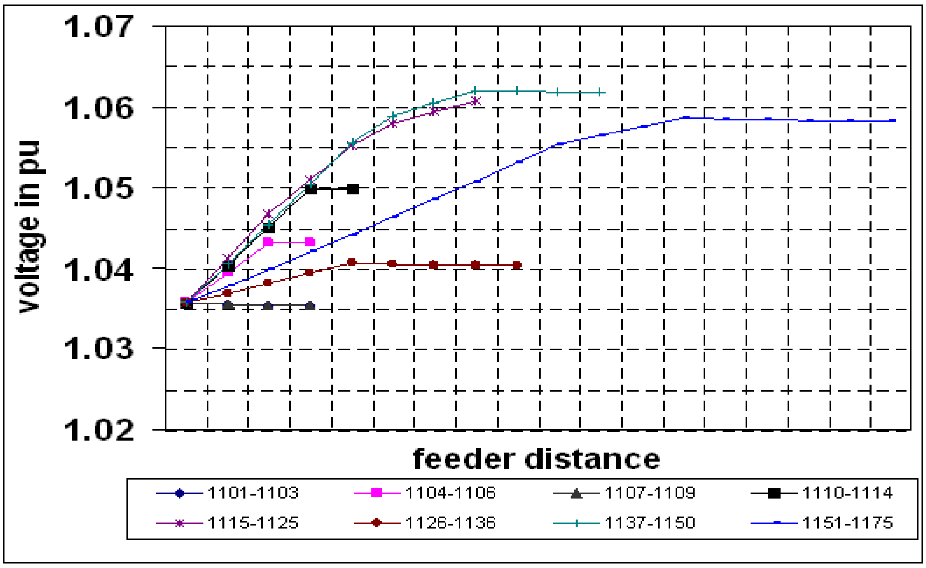


Figure 87. Voltage profile of each feeder using conventional AVC relay

From Figure 87, it can be seen that the voltage of furthest DG connection point at feeders from bus $B_{1137-1150}$ (green line) and $B_{1115-1125}$ (purple line) are over the upper limit of 1.06 pu. However, the voltage of sending-end busbar V_S required to be reduced and conventional OLTC voltage control cannot solve this problem due to that the measured voltage of sending-end busbar V_S which is 1.036 pu is within the deadband of 1.03 pu, which is the initial reference voltage setting point V_{SET} of AVC relay. The DG connected in the bus $B_{1137-1150}$ and $B_{1115-1125}$ must be disconnected to avoid overvoltage, therefore the DG capacity can be connected in this network is 8.65MW.

The generic distribution network was developed in Simulink of MATLAB® as shown in Figure 88 to demonstrate the advanced compensation-based OLTC voltage control algorithm using ACVC technique. The network data was provided to the control decision maker by off-line power flow calculation. The initial time delay is 10-60 seconds from the overvoltage/undervoltage situation detected to the tap changing signal issued in common practice at present and for demonstration purpose the initial delay is set 5 seconds. The time delay between two tap changing operations was 1 second.

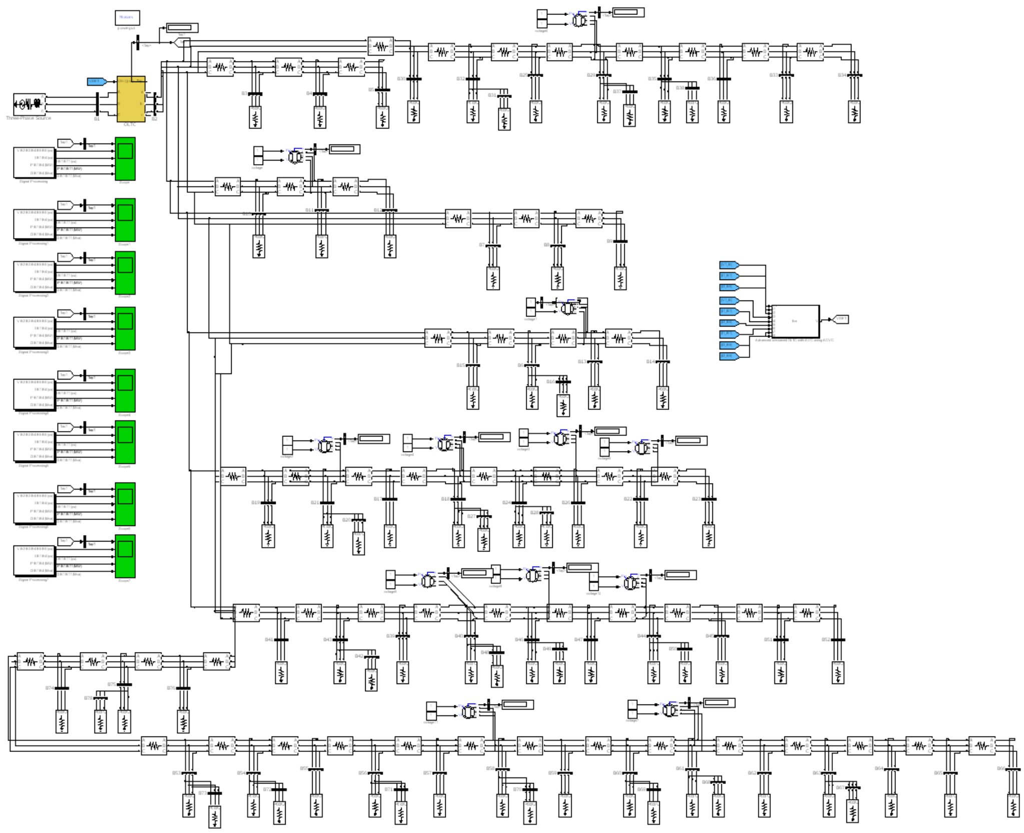


Figure 88. Simulink model of generic distribution network

The voltage rise is detected by ACVC and a new reference voltage setting point V_{SET}, was calculated as 1.022 pu. The voltage of sending-end busbar was 1.036 pu which is out of the deadband of new setting thus a tap down operation is implemented by OLTC. When the voltage of sending-end busbar is reduced to 1.021 pu, the voltage profile of two overvoltage feeders is shown as Figure 89. The voltage of DG connection point at B_{1121} and B_{1143} were reduced to 1.045 pu and 1.047 pu respectively which were within 1.06 pu upper limit. No power curtailment of DG occurs and the DG capacity is 20.76MW when the advanced compensation-based OLTC voltage control algorithm is implemented.

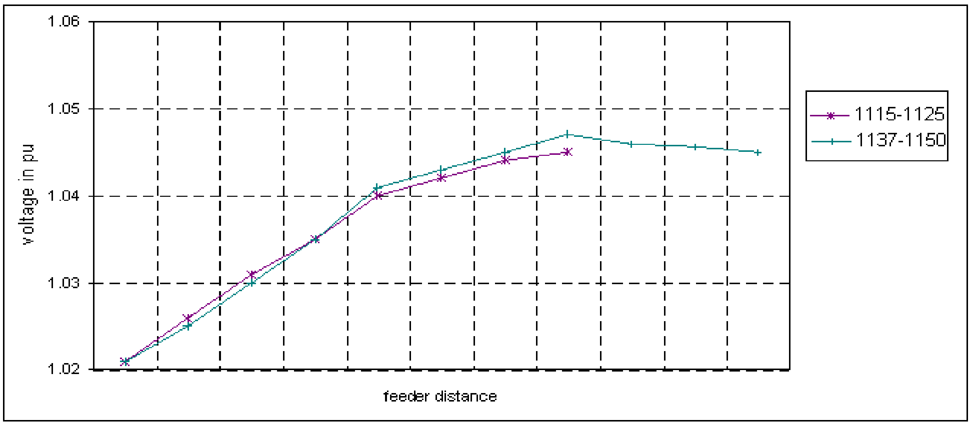


Figure 89. Voltage profile of the two affected feeders using advanced compensation-based OLTC voltage control algorithm

When each DG output power is increased from 1.73 to 3.46MW under the same minimum load condition whose data is shown in Table 19, the voltage profile of each feeder using conventional OLTC voltage control is shown as Figure 90. The initial reference voltage setting point V_{SET} of AVC relay is 1.03 pu with 2% deadband.

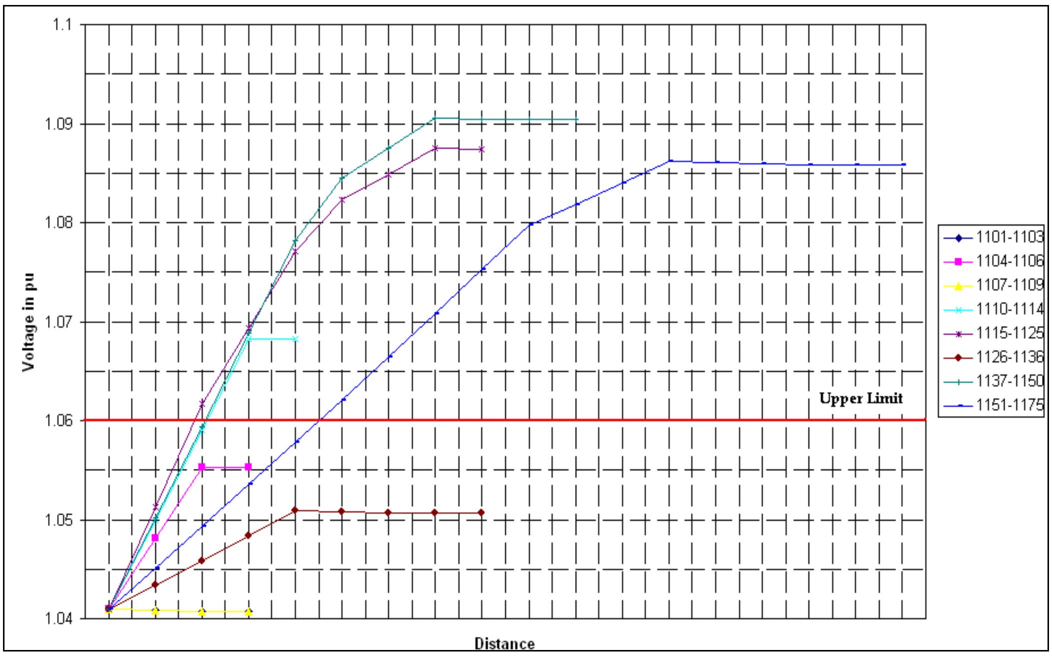


Figure 90. Voltage profile using conventional OLTC voltage control

From Figure 90, it can be seen that four feeders $B_{1137-1150}$ (green line), $B_{1110-1114}$ (ice blue line), $B_{1115-1125}$ (purple line) and $B_{1151-1175}$ (blue line) have overvoltage due to the large DG output and the minimum load condition. Since conventional OLTC voltage control measures the sending-end voltage of transformer V_S, which is 1.041 pu and compared with reference voltage setting point V_{SET} 1.03 pu, no tap changing is operated and the overvoltage of these four feeders are uncontrollable. To avoid overvoltage, the DG connected to these four feeders must be disconnected and the DG capacity is 6.92MW.

The voltage profile of each feeder using advanced compensation-based OLTC voltage control algorithm with ACVC technique is simulated and the results are shown in Figure 91.

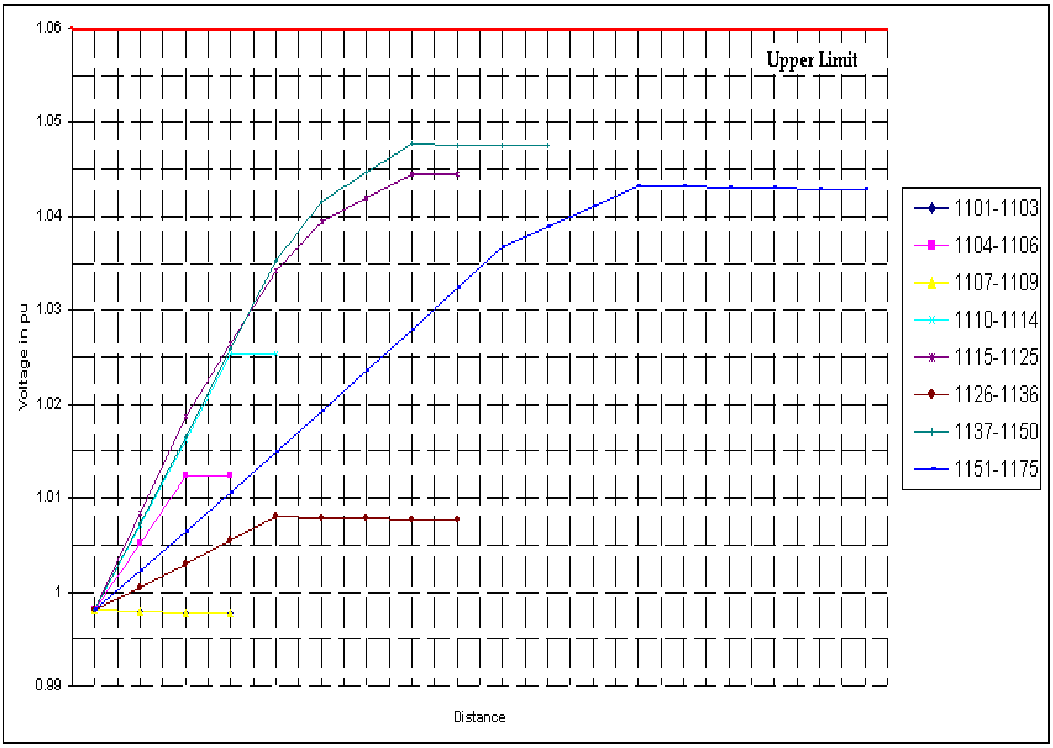


Figure 91. Compensation-based algorithm performance

It can be seen that the voltage of sending-end busbar has been reduced to the new reference voltage setting point V_{SET} as 1.002 pu by ACVC technique. After three tap down operations, the voltage of sending-end busbar V_S is 0.998 pu which is within the deadband of new setting point in AVC relay. The voltage of every bus is now within the statutory limits. The DG capacity is increased to 41.52MW using the advanced OLTC voltage control algorithm as shown in Table 21. The capacity of DG that can be connected to the networks can be increased further.

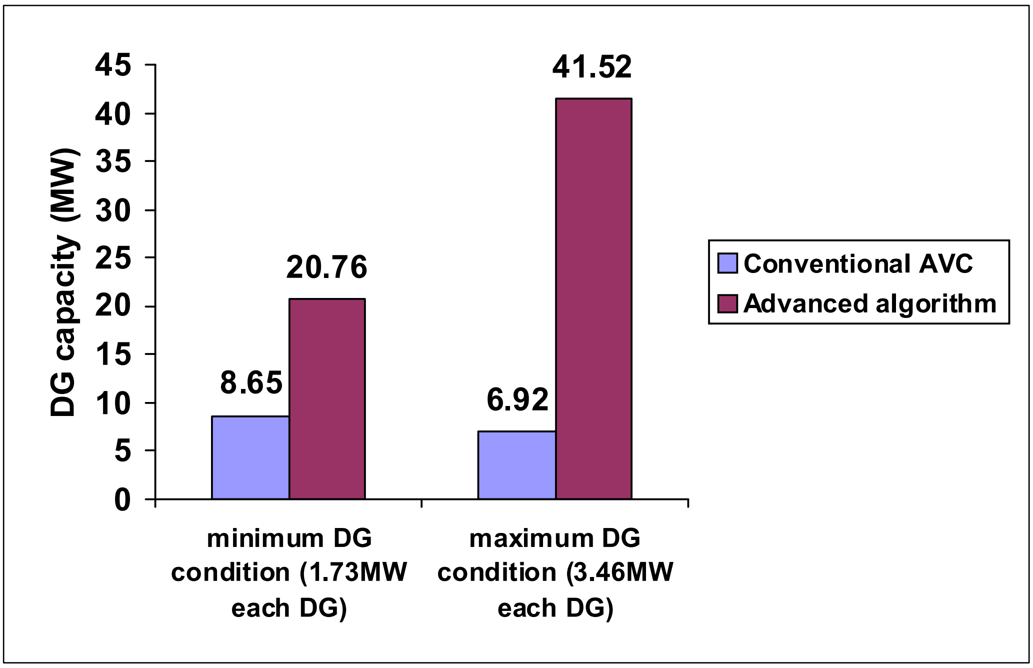


Table 21. DG capacity using advanced algorithm

The results shown in above simulations and Table 21 demonstrate that the advanced compensation-based OLTC voltage control algorithm have a better voltage control performance and the DG capacity which can be connected to 11kV distribution network is increased significantly.

7.3 Comparison with other advanced methods

There are some developed OLTC voltage control methods to accommodate DG penetration in distribution networks by other researchers which are introduced in Section 5.5. M. Fila and G. Taylor from Brunel University proposed a SuperTAPP n+ relay to offer OLTC voltage control performance in distribution networks with DG [3]. H. Leite and H. Li from Manchester University proposed an Automatic Voltage Reference Setting (AVRS) technique to operate OLTC voltage control in distribution networks [152]. These two advanced methods are selected to compare the performance with the advanced compensation-based OLTC voltage control algorithm using ACVC method under similar network conditions.

7.3.1 Comparison with SuperTAPP n+ relay

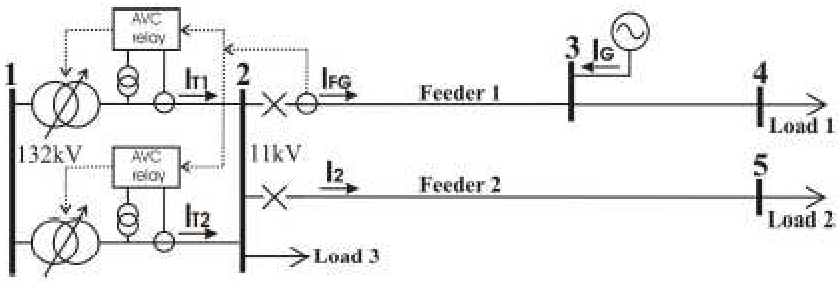


Figure 92. One-line diagram of 132/11kV distribution network [3]

This network consists of a 132kV grid, two 132/11kV OLTC transformers, SuperTAPP n+ relay, and first feeder with one DG operating at constant unity power factor at Bus 3 with a load at the end of the feeder Bus 4. The second feeder has a load connected at the remote end of the feeder Bus 5 as shown in Figure 92. The total rated capacity of DG is 5MW and the maximum load demand is 50MVA and minimum load condition is 15MVA with 0.96 power factor. The voltage value of essential points under various load and DG conditions are simulated in [3] and the results are presented in Figure 93.

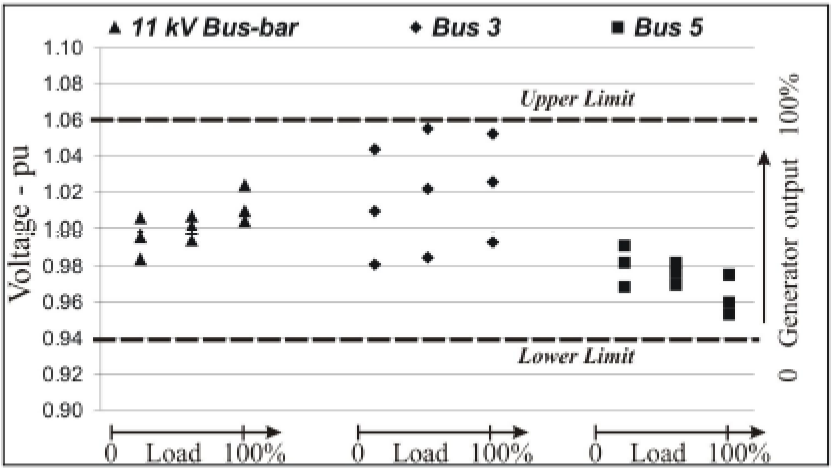


Figure 93. Performance of SuperTAPP n+ relay [3]

From Figure 93, it can be seen that the SuperTAPP n+ relay can control the voltage effectively under maximum DG generation 5MW minimum load condition and minimum DG generation 0MW maximum load condition.

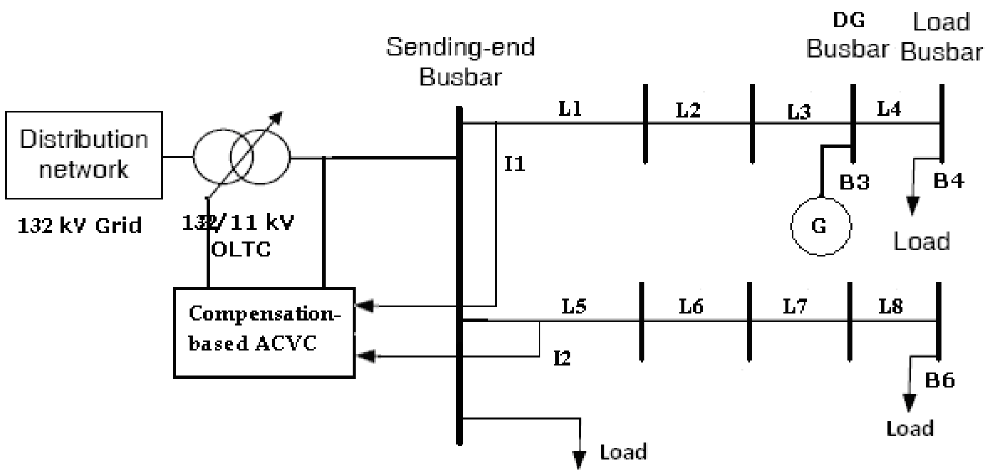


Figure 94. Similar network using compensation-based ACVC

The advanced compensation-based OLTC voltage control algorithm are simulated with a similar network in Figure 94 and the load and DG condition is using the same value as in SuperTAPP n+ relay case as Figure 92. The voltage performance is presented in Figure 95 and Figure 96. The voltage of DG connection point and voltage of load at the end of feeder 2 are selected to do the comparison under maximum DG generation 5MW minimum load condition and minimum DG generation 0MW maximum load condition.

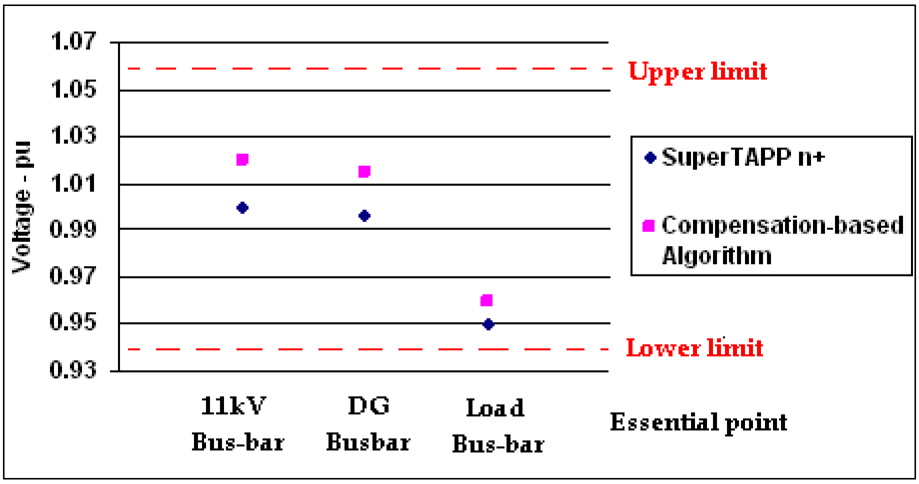


Figure 95. Performance under maximum DG and minimum load

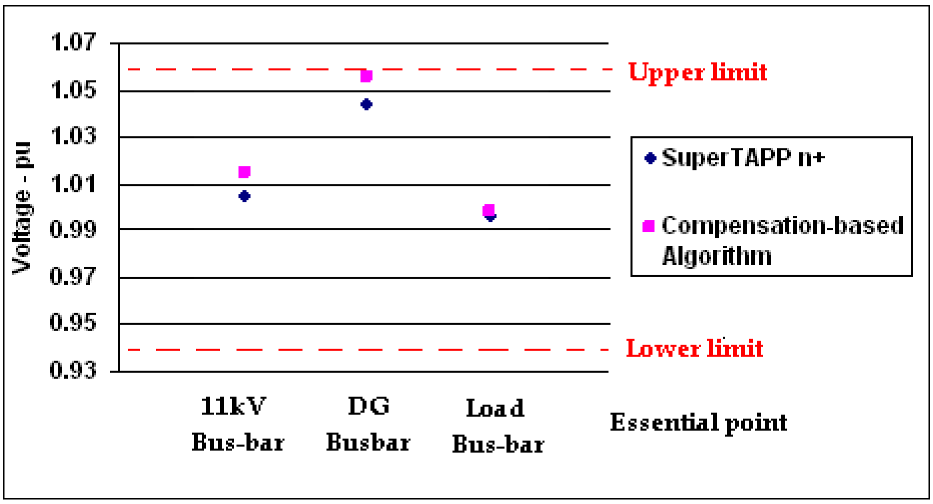
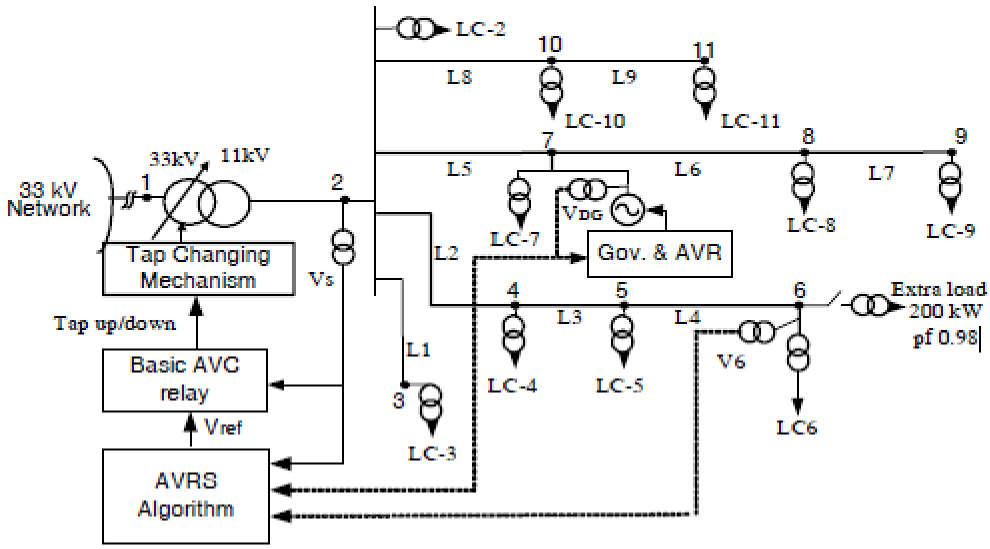


Figure 96. Performance under minimum DG and maximum load

From Figure 95 and Figure 96, it can be seen that the advanced compensation-based OLTC voltage control algorithm can perform correctly under the similar network conditions and the voltage level is a little higher than the voltage using SuperTAPP n+ relay because there is no tap changing operation when the voltages are within limits in order to reduce the number of changing operation.

7.3.2 Comparison with AVRS algorithm

The 11kV distribution network shown in Figure 97 was modelled to evaluate the voltage control performance of AVRS algorithm.



Where: LC:– Load centre, L – Line , DG:– Distributed generation
AVRS: – Automatic voltage reference setting

Figure 97. 11kV distribution network using AVRS algorithm [152]

This network has a 33kV grid source, a 33/11kV OLTC transformer, five feeders, eleven load buses, an AVC relay with AVRS device and one DG at LC-7. The line impedance parameters and load conditions are listed in Table 22 [152].

Table 22. Line impedance and load conditions [152]

Line	Impedance (Ω)	Load	Min (kVA/pf 0.98)	Max (kVA/pf 0.98)
L1	13+j1.0	2	5.1	4.7
L2	4.1+j1.0	3	55.1	220.4
L3	4.1+j1.0	4	8.2	33.7
L4	11.1+j4.9	5	70.4	280.6
L5	2.2+j1.3	6	5.1	55.1
L6	11.1+j4.9	7	55.1	220.4
L7	5.8+j2.6	8	25.6	104.1
L8	0.4+j0.12	9	9.2	35.7
L9	2.2+j1.7	10	10.2	41.8
		11	9.2	36.7

The simulation results obtained from paper [152] are presented in Figure 98 and Figure 99. The voltages of three essential points are shown under minimum and maximum load conditions with different DG generation.

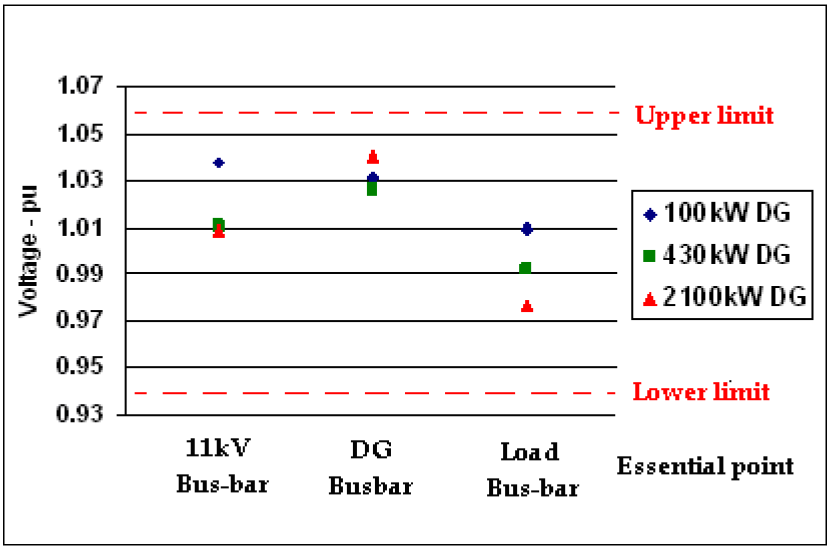


Figure 98. Performance of AVRS algorithm under maximum load

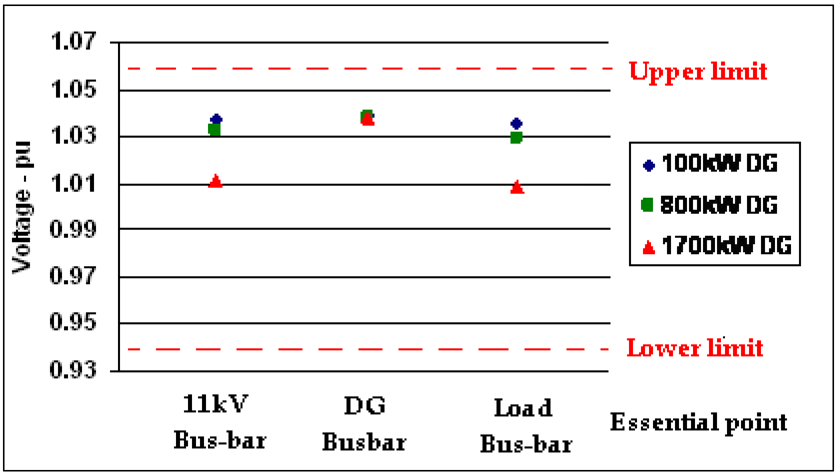


Figure 99. Performance of AVRS algorithm under minimum load

The advanced compensation-based OLTC voltage control algorithm using ACVC is simulated with a similar network in Figure 100. The line impedance parameters and load conditions are the same as the Table 22.

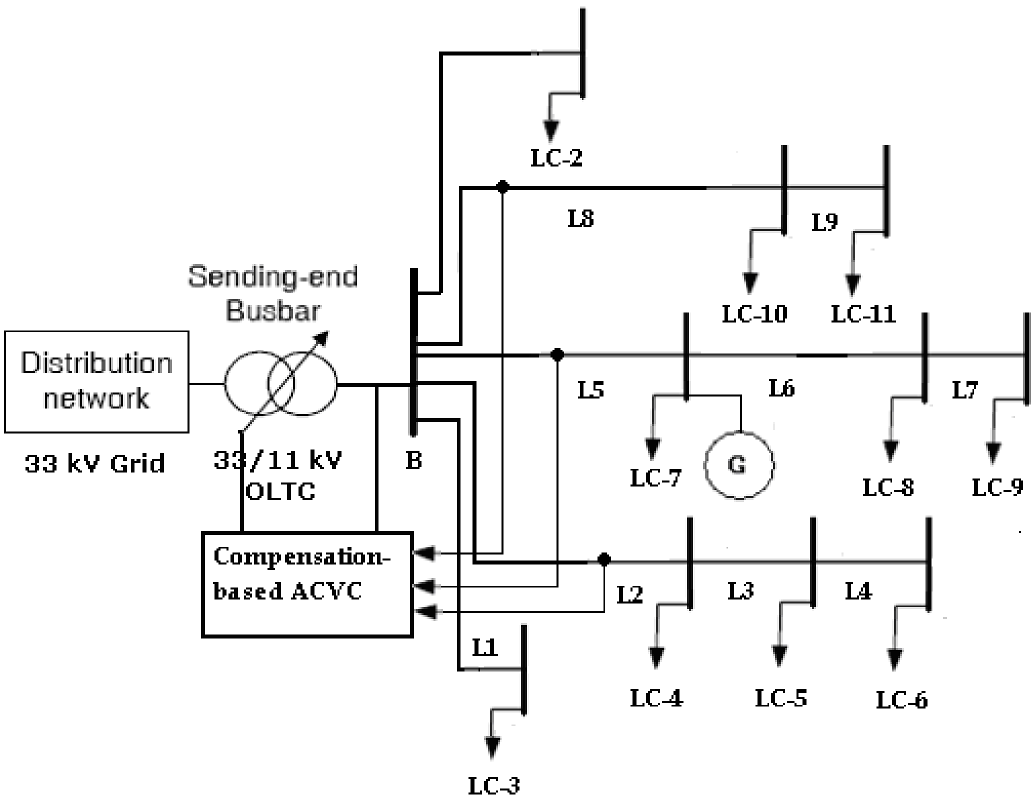


Figure 100. 11kV network using compensation-based algorithm

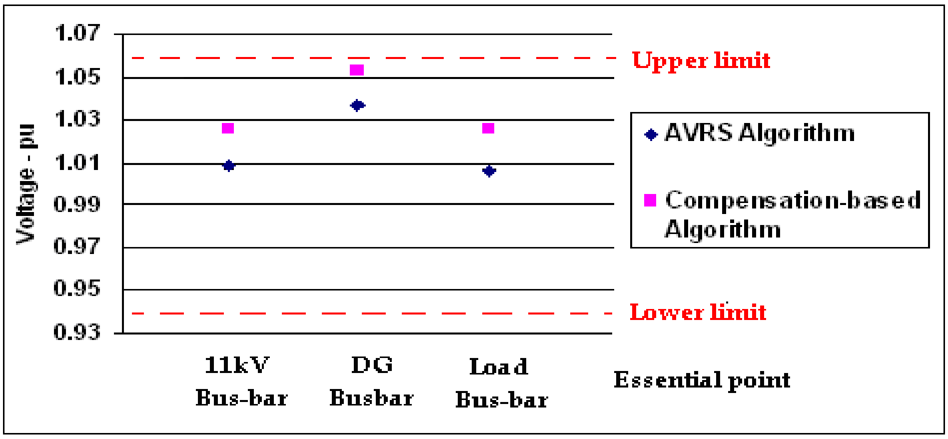


Figure 101. Performance under maximum DG and minimum load

The voltage control performance of compensation-based algorithm under maximum DG and minimum load condition is presented in Figure 101 to compare with the voltage of AVRS algorithm. The compensation-based algorithm can perform correctly and have a similar performance as AVRS algorithm under different network conditions.

7.4 Summary

The performance of advanced compensation-based OLTC voltage control algorithm using ACVC technique is demonstrated under different distribution network conditions using Simulink. The simulation results obtained described in the above cases show that the advanced compensation-based OLTC voltage control algorithm using ACVC technique, can provide an accurate voltage setting point for the existing AVC relay to control the voltage of the sending-end busbar as well as the remote points of feeders in 11kV distribution network. The capacity of DG that may be connected to multiple feeders can be increased while unacceptable voltage rises at the DG connection points can be avoided.

Chapter 8

Conclusions

It is a legal requirement in the UK for Distribution Network Operators to regulate the voltage and maintain it within statutory limits for consumers across a range of conditions such as varying load or integration of distributed generation. The On-Load Tap Changer transformer controlled by Automatic Voltage Control relay is the widely used voltage control device operating between multiple voltage levels. In high voltage distribution networks, the OLTC transformer with AVC relay is expected to continue in service as the main voltage control device for many years.

The small and medium scale DG connected to distribution networks is attracting more and more attention due to various advantages. In the past two decades, the total DG capacity has grown from 1.2GW to over 12GW in England and Wales. In addition, DG penetration is continuing to grow by a rapidly growth rate to meet the emission reduction target of government since most of DG resources are from renewable energy. However, a high penetration level of DG of different capacity and location connected to distribution networks can impact on the operation, control, reliability of the distribution networks significantly and hence DNOs are going to face a number of new challenges with voltage control.

8.1 Overview of conventional OLTC voltage control, DG technologies and future voltage control using Smart Meters

This thesis has reported investigation into voltage control using OLTC transformer in distribution networks with DG penetration. The background information of distribution network and OLTC operation has been introduced in Chapter 2. A general overview of conventional OLTC voltage control schemes which are used to control the voltage in distribution networks without the presence of DG has been given. It has been shown how Line Drop Compensation (LDC) technique is used to compensate the voltage drop from substation to feeder end. When OLTC transformers of different voltage levels are operated in series, Grading Time (GT) is used to ensure the up-stream OLTC has completed operation before down-stream OLTC operation. Some enhanced schemes which reduce the delay time are simulated in Simulink to compare with GT scheme. Methods designed to provide for parallel operation of OLTC transformers has also been listed. Some relevant voltage control methods using other devices are provided.

Various DG technologies have been reviewed in Chapter 3 with their sizes, capacity, potentials, main barriers and output power characteristics. The economics of competitive DG technologies can result in the further growth of DG penetration level in distribution networks. A range of renewable DG technologies are developed driven by the higher fossil fuel cost and limited availability, emission reduction target of government and economical of renewable resources.

Future voltage control using Smart Meters in Smart Grid have been discussed in Chapter 4. This provides an overview of the basic concept of Smart Grid and the intelligent functions of Smart Meter in the UK. The voltage control needs to be more flexible and smarter in the future Smart Grid to accommodate high level of DG penetration and Smart Grid applications. The potential voltage control by Smart Meters in distribution networks of Smart Grid has been investigated. The Smart Meter could be used as a voltage sensor and monitor to offer voltage information to control centre by two-way communication of Smart Metering system.

A selection of different communication technologies has been investigated to determine the availability of each communication technology for suitable voltage levels from voltage control point of view. An example of generic urban distribution network using selected communication technologies has been used to demonstrate the latency of decentralized control structure. The analysis of latency and cost of these communication infrastructures has shown that the real-time voltage control using Smart Meters is impossible to be cost-effectively achieved by centralized control structure of Smart Metering system in the UK and recommended decentralized control structure due to the large amount of data, the limited capability of existing communication technologies, high latency and the costs.

8.2 DG impact on OLTC voltage control

The analysis of DG impacts on OLTC voltage control in conventional 11kV distribution networks has been carried out in Chapter 5. Simulation results from a series of Simulink models have been shown that a large amount of power exported from DG can cause the voltage of DG connection point to go outside of the statutory limits. Moreover, the bidirectional direction of power flow can either be from power grid towards loads, or vice versa when DGs are connected. It has been shown that a limited LDC function operated with reverse power flow using conventional voltage control methods will cause voltage control problems. The X/R ratio of different distribution lines have also been simulated to demonstrate that the reactive power voltage control is less effective in distribution networks. Conventional OLTC voltage control methods have limitations with increasing penetration of DG. These voltage control problems must be critically assessed and solved before DG can be connected to distribution networks. New enhanced OLTC voltage control schemes of other researchers to accommodate DG penetration have been included with a brief discussion of their advantages and disadvantages.

8.3 Advanced compensation-based OLTC voltage control algorithm using ACVC technique

To maintain the voltage of all loads within the certain limits and at the same time overcome the restriction placed on DG capacity, DNOs require a more active voltage control algorithm that can be adopted for the short-term or medium-term distribution network conditions without significant reinforcement. An advanced compensation-based OLTC voltage control algorithm using Automatic Compensation Voltage Control (ACVC) technique has been proposed in Chapter 6. The proposed method has a better voltage control performance than conventional method since each feeder is considered separately and not just uses composite line impedance for all feeders in conventional method. The voltage of sending-end busbar and voltage compensation of every feeder are inputted to the decision maker which uses advanced compensation-based OLTC voltage control algorithm. The new reference voltage setting point is calculated and provided to AVC relay dynamically to implement the OLTC in order to control the voltage profile along each feeder is within the statutory limits.

The performance of proposed algorithm has been demonstrated under different load and DG conditions using Simulink of MATLAB software in Chapter 7. The simulation results obtained have shown that the advanced compensation-based voltage control algorithm can provide an accurate reference voltage setting point dynamically for AVC relay to control the voltage of sending-end busbar as well as remote points of feeders in 11kV distribution network while maximising DG output power. Using this technique the capacity of DG that can be connected to multiple feeders is increased while the unacceptable voltage rise at DG connection point has also been controlled. A generic 11kV distribution network which is more complicated than most systems from the UKGDS has been modelled to demonstrate the proposed compensation-based OLTC voltage control algorithm. It has been shown that it provides an improved control performance for practical 11kV distribution networks without any remote monitors and communication networks. A comparison study of two most recent developed methods by other researchers also shows that the proposed advanced compensation-based OLTC voltage control algorithm using ACVC method has a correct performance under similar conditions while this proposed method is not depending on the remote monitoring or communication network and can be easily to implement to increasing the utilisation of existing distribution network while offer a cost-effective option to support more DG capacity.

8.4 Novelties of the proposed algorithm development

The proposed ACVC technique is based on AVC relay with LDC function. The voltage of sending-end busbar and current of each feeder are locally measured at the substation level without remote monitor units or communication links. Voltage compensation for each feeder is simulated by using each feeder current and line impedance. The power flow direction of each feeder is considered to determine that the voltage compensation of each feeder is voltage drop from sending-end busbar to feeder end or voltage rise from sending-end busbar to the furthest DG connection busbar. Therefore, these separate feeder compensations can eliminate the voltage error caused by LDC when the power flow is reversed.

The proposed algorithm performs correctly under variation of load, DG and line parameter changes shows the robustness of this method to be implemented by the DNOs. The DG capacity of the simulation case study using the 75-bus generic 11kV distribution network is increased from

8.65MW to 20.76MW under minimum load, minimum DG condition, 6.92MW to 41.52MW under minimum load, maximum DG condition. Since the proposed algorithm only uses local measurement from substation sending-end busbar without any remote monitors or communication links, it can be installed easily and cost-effectively to the distribution network using the existing voltage control devices. The greater amount of DG capacity connected into the distribution networks contributes to the carbon emission reduction plan of government.

Chapter 9

Future works

The future research work can be taken to extend the work conducted in this thesis in following ways:

1. The advanced compensation-based OLTC voltage control algorithm using ACVC technique in Chapter 6 is a local voltage control method using OLTC which can be operated coordinated with other voltage control devices such as line voltage regulator, static var compensator and shunt capacitor. An effective control algorithm for coordinated operation is required to improve the voltage control performance in distribution networks. The extensive deployment of "smart" applications across distribution networks will offer the potential opportunity to support the coordinated voltage control. This needs investigation and potential weaknesses examined.

2. The state estimation of distribution networks can be used with voltage control algorithm to improve the control performance. The control method of this thesis is based on the assumption that all of the network data can be obtained by off-line power flow calculation. The state estimation will provide a more active and dynamic control when accurate algorithms are implemented. In Chapter 4, remote monitoring is

investigated that the existing communication technologies are inadequate to support real-time voltage control due to the volume of data and high latency times. However, remote monitoring of some critical points could provide some voltage measurements to be used with a state estimator to enhance the accuracy level with a cost-effective communication infrastructure. An investigation into an accurate algorithm for state estimation could prove valuable.

3. The delayed measurements from sensors could be used to improve the voltage control performance for decentralized voltage control in the future Smart Grid. The delayed information of demand and generation can be used with historical data in order to estimate the near future state of the network. An optimization program could provide a valuable tool to effectively manage input data and then provide proper control signals to a selection of voltage control devices.

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6. "Advanced compensation-based OLTC voltage control in distribution networks with DGs" journal paper has been submitted to IEEE Transaction on Power system, 2013. (Revised and resubmitted)

Appendix A

Standard Newton-Raphson power flow algorithm in Matpower software package [1]

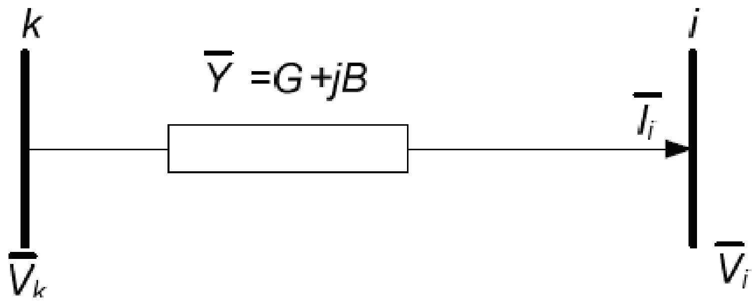

Figure 1. Two busbar section of distribution network

The Newton-Raphson algorithm is used to solve power flow calculation [2]. For a network with n number of nodes, the power injection measurement of node i can be written as follows:

$$I_i^* = \sum_{k=1}^{n} Y_{ik}^* V_k^* \qquad S_i = V_i I_i^* = V_i (\sum_{k=1}^{n} Y_{ik} V_k)^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^*$$

$$Y_{ik} = G_{ik} + jB_{ik} \qquad V_i = |V_i| \angle \theta_i = |V_i| (\cos\theta_i + j\sin\theta_i)$$

The complex power equation can be rewritten as:

$$S_i = P_i + jQ_i = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* = \sum_{k=1}^{n} |V_i||V_k| (\cos\theta_{ik} + j\sin\theta_{ik})(G_{ik} - jB_{ik})$$

Resolving into the real and imaginary parts as power balance equations:

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di}$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = Q_{Gi} - Q_{Di}$$

Neglecting line charging capacitance, power flow between two nodes can use voltage magnitude and phase angle to express:

$$x = \begin{bmatrix} \theta_2 \\ \vdots \\ \theta_n \\ |V_2| \\ \vdots \\ |V_n| \end{bmatrix} \qquad f(x) = \begin{bmatrix} P_2(x) - P_{G2} + P_{D2} \\ \vdots \\ P_n(x) - P_{Gn} + P_{Dn} \\ Q_2(x) - Q_{G2} + Q_{D2} \\ \vdots \\ Q_n(x) - Q_{Gn} + Q_{Dn} \end{bmatrix}$$

The power flow Jacobian Matrix is determined by differentiating each function with respect to each variable as:

$$J(x) = \begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \frac{\partial f_1(x)}{\partial x_2} & \cdots & \frac{\partial f_1(x)}{\partial x_n} \\ \frac{\partial f_2(x)}{\partial x_1} & \frac{\partial f_2(x)}{\partial x_2} & \cdots & \frac{\partial f_2(x)}{\partial x_2} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial f_n(x)}{\partial x_1} & \frac{\partial f_n(x)}{\partial x_2} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \end{bmatrix}$$

Make an initial guess of x and using the below procedure to solve power flow:

$$While \quad \left\| f(x)^n \right\| > \varepsilon \quad Do$$
$$x^{(k+1)} = x^{(k)} - J(x^{(k)})^{-1} f(x^{(k)})$$
$$k = k + 1$$
$$End \quad While$$

References

[1] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "Matpower: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," Power Systems, IEEE Transactions on, vol. 26, no. 1, pp. 12-19, Feb. 2011.

[2] "Newton-Raphson Power Flow". Available at

http://eee.guc.edu.eg/Courses/Electronics/ELCT908%20Distributed%20Power%20Systems/Lectures/NR_power%20Flow.pdf.

Appendix B